Final Report

Certification and In-Use Compliance Testing for Heavy-Duty Diesel Engines to Understand High In-Use NOx Emissions

Contract No. 15RD001

Prepared for:

Dr. Yi Tan
California Air Resources Board
Research Division
1001 I street
Sacramento, CA 95812
(916) 324-7903

November 2018

Dr. Thomas D. Durbin, PI
Dr. Kent C. Johnson, Co-PI
Dr. Georgios Karavalakis, Co-PI
Dr. Yu (Jade) Jiang
Mr. Jiacheng (Joey) Yang

University of California
CE-CERT
Riverside, CA 92521
951-781-5791
951-781-5790 (fax)

Acknowledgments

The authors thank the following organizations and individuals for their valuable contributions to this project.

We acknowledge funding from the California Air Resources Board under contract 15RD001.

We acknowledge Mr. Mark Villa, Mr. Don Pacocha, and Mr. Edward O'Neil of the University of California, Riverside for their contributions in conducting the emissions testing for this program.

Table of Contents

List of Tables

List of Figures

Abstract

Given the importance of achieving reductions of oxides of nitrogen (NOx) emissions from heavy-duty diesel engines (HDDEs) over the road, it is important to investigate the differences between the certification and in-use emission rates and to understand the factors contributing to these differences. For this program, two heavy-duty diesel vehicles (HDDVs) equipped with 2010-compliant HDDEs from different manufacturers with diesel particulate filter (DPF) and selective catalytic reduction (SCR) technologies were tested using an engine-dynamometer, a chassis-dynamometer, and over the road. Testing was conducted over a number of different cycles and driving conditions, including both urban and freeway driving, to evaluate the impact of engine and vehicle operations on NOx emissions. Based on findings from this study, the effectiveness of the current HDDE certification and HDDV in-use compliance procedures was evaluated for possible enhancements or alternatives of those procedures.

The results show that NOx emission rates for HHDVs varied over different driving conditions, and between trucks/engines. The emission rates for cycles representing urban driving conditions were generally higher those for the freeway driving conditions. The values for urban cycles ranged from 0.16 to 1.05 g/bhp-hr, depending on the vehicle and the specific driving cycle, with emissions for the Urban Dynamometer Driving Schedule (UDDS) and Federal Test Procedure (FTP) ranging from 0.21 to 0.82 g/bhp-hr. NOx emissions for most of the urban cycles were higher than the 0.2 g/bhp-hr NOx standard. NOx emissions from the freeway driving conditions were on the order of 0.2 to 0.3 or less g/bhp-hr. Interestingly, the NOx emissions for the engine dynamometer testing were generally lower than those for the chassis dynamometer and on-road testing for the same UDDS driving conditions. For one truck/engine, the manufacturer attributed this to the engine was operating a cold start mode that retarded the engine timing during the engine testing. For the other truck/engine, these differences were attributed to differences in SCR temperatures and the SCR efficiency in reducing NOx emissions.

The on-road freeway driving test results were evaluated based on the Not-to-Exceed (NTE) requirements in the United States (U.S.) and the work-based Moving Averaging Window (MAW) requirements in Europe. For the on-road testing, the fraction of in-use operation that met the criteria for valid NTE events ranged from 4.0 to 50.2%, while essentially all of the operation met the criteria for valid MAW windows. Average emissions for passing NTE events ranged from 0.09 to 0.24 g/bhp-hr for one truck and from 0.29 to 0.41 g/bhp-hr for the other truck, while failing NTE events ranged from 0.71 to 1.12 g/bhp-hr and 0.72 to 0.83 g/bhp-hr, respectively, for the two trucks. Based on the NTE criteria, one truck passed 7 of 9 test segments, while the other passed only 3 of 9 test segments. For the MAW test, the emissions were found to fail for a majority of the routes for both trucks. Average emissions for passing MAW windows ranged from 0.08 to 0.15 g/bhp-h for one truck and from 0.20 to 0.24 g/bhp-h for the other truck, while failing MAW windows ranged from 0.54 to 0.70 g/bhp-h and 0.44 to 0.52 g/bhp-h, respectively, for the two trucks. The percent of failing NTE events ranged from 22 to 89% and the percent of failing MAW ranged from 6 to 80%.

Overall, the results of this study suggest that in-use NOx emissions can be higher than what might be expected based on certification testing and in-use testing requirements. Differences between different types of laboratory and on-road testing could be attributed to factors that impact engine out NOx and the SCR catalyst performance, which in turn contribute to differences in tailpipe NOx emissions. The results suggest that further investigation is warranted to better understand differences between NOx emissions obtained during certification testing and real-world operation, and how gaps can be narrowed moving into the future.

Acronyms and Abbreviations

ASTM....................................American Society for Testing and Materials
APU....................................auxiliary power unit
CARB....................................California Air Resources Board
CE-CERT....................................College of Engineering-Center for Environmental Research and Technology (at the University of California, Riverside)
CF....................................conformity factor
CFR....................................Code of Federal Regulations
CO....................................carbon monoxide
COV....................................coefficient of variation
CO_2....................................carbon dioxide
CPC....................................condensation particle counter
CVS....................................constant volume sampling
DEF....................................diesel emissions fluid
DI....................................direct injection
DMM....................................Dekati Mass Monitor
DOC....................................diesel oxidation catalyst
DPF....................................diesel particulate filter
ECM....................................engine control module
EGR....................................exhaust gas recirculation
EMA....................................Truck and Engine Manufacturers Association
EPA....................................United States Environmental Protection Agency
FID....................................flame ionization detector
FTP....................................Federal Test Procedure
HDDV....................................heavy-duty diesel vehicle
HDDE....................................heavy-duty diesel engine
HDIUC....................................Heavy-Duty In-use Compliance testing
HHDDT....................................Heavy Heavy-Duty Diesel Truck
hp....................................horsepower
IAT....................................Intake Air Manifold Temperature
IDI....................................indirect injection
kW....................................kilowatt
lpm....................................liters per minute
LNT....................................lean NO_X trap
MAW....................................Moving Average Window
MECA....................................Manufacturers of Emissions Controls Association
MEL....................................Mobile Emission Laboratory
MY....................................model year
NTE....................................Not-to-Exceed
NMHC....................................non-methane hydrocarbons
NO_X....................................oxides of nitrogen
OBD....................................on-board diagnostics
OEM....................................original equipment manufacturer
OHMS....................................On-Road Heavy-Duty Emissions Measurement System
PDP-CVS....................................positive displacement pump - constant volume sampling
PEAQS....................................PEAQS
PEMS....................................portable emissions measurement systems
PM....................................particulate matter

PN ....particle number
QC...quality control
RIA..Regulatory Impact Analysis
RMC..Ramped Modal Cycle
RPM..revolutions per minute
ROG..reactive organic gases
RSD...remote sensing device
scfm...standard cubic feet per minute
SCR...selective catalytic reduction
SCRT...selective catalytic reduction technology
SET ....supplementary emissions test
SHED ....evaporative emission
SOF ....soluble organic fraction
THC...total hydrocarbons
TWC..three way catalyst
UCR ....University of California at Riverside
UDDS..Urban Dynamometer Driving Schedule
ULSD ....ultralow sulfur diesel

Executive Summary

Although considerable progress has been made in reducing the contributions of vehicle emissions to the emissions inventory and in improving air quality, further reductions in oxides of nitrogen (NOx) emissions are still needed to achieve future air quality goals in California. In an effort to reduce emissions from heavy-duty diesel vehicles (HDDVs), regulatory agencies have tightened laboratory certification limits and have implemented not-to-exceed (NTE) in-use testing requirements. While significant steps have been taken to reduce NOx emissions from HDDVs, their effectiveness remains largely unknown. The goal of this study was to evaluate the effectiveness of current HDDE certification and HDDV in-use compliance procedures for controlling in-use NOx emissions from HDDVs and to suggest possible changes to these procedures that could facilitate California in meeting ambient air quality standards for ozone and PM.

Two 2010-compliant heavy-duty diesel engines (HDDEs) equipped with diesel particulate filter (DPF) and selective catalytic reduction (SCR) technologies and from different manufacturers were tested for emissions using an engine-dynamometer, a chassis-dynamometer, and on-road. The engines included a 2014 model year (MY) engine from Manufacturer A and a 2013 MY engine from Manufacturer B, both equipped in their own truck chassis. Emissions testing for this study included initial chassis-dynamometer testing, on-road testing, an engine-dynamometer test conducted with the engine removed from the truck chassis, and then final chassis-dynamometer testing to provide a comparison with the initial chassis test conducted prior to removing the engine.

Literature Review

A literature review was conducted to better understand methods that are used to characterize emissions from heavy-duty vehicles, and to understand the NOx emissions rates of in-use heavy-duty diesel vehicles with these methodologies. A variety of techniques used to evaluate in-use emissions of heavy-duty diesel vehicles were reviewed, including chassis/engine dynamometer testing, on-road PEMS testing, and other techniques such as remote sensing devices (RSD), probe-based methodologies, tent-like systems such as the On-Road Heavy-Duty Emissions Measurement System (OHMS), and the Portable Emissions AcQuisition System (PEAQS). Currently, a greater emphasis is being put on measurement methods that either characterize emissions on the road, or over driving cycles that are representative on real-world driving conditions on a chassis dynamometer. Chassis and engine dynamometer results have shown that NOx emissions vary considerably from cycle to cycle and for different vehicles/engines. NOx emissions are lowest for higher speed cruise cycles where the higher exhaust temperatures provide more optimal SCR performance. More transient/stop-and-go cycles, such as the Urban Dynamometer Driving Schedule (UDDS), tend to show higher emissions. The emissions from more moderate cycles are often higher than the typical certification values when characterized on a g/bhp-hr basis, which can be due to a number of different factors, including the temperature of the SCR aftertreatment system and differences in the load level and profile of the cycle compared to the certification test. The results from on-road PEMS and other measurement studies have also shown that NOx emissions for different types of driving can often be higher than certification NOx levels and that disproportionately higher NOx emissions are generated under lower load operating conditions. Studies of NTE operation have also shown that a large fraction of in-use operation does not meet the criteria for a valid NTE events, in terms of operating within the NTE zone for a period of at least 30 seconds with the aftertreatment system temperature above 250°C. Results from roadside measurement methods designed to survey a larger number of vehicles, including RSD, probe-based methodologies, OHMS, and PEAQS, have also shown that there is an important fraction of high emitting trucks that contribute a disproportionate amount of NOx.

Vehicle and Engine Testing

Table ES-1 provides a summary of test cycles for the different test conditions. Based on vehicle and engine operating conditions, test cycles were classified based on whether they were more representative of urban or freeway driving. The urban cycles included the Urban Dynamometer Driving Schedule (UDDS), the California Air Resources Board's (CARB's) Heavy Heavy-Duty Diesel Truck (HHDDT) test transient cycle, and the Federal Test Procedure (FTP). Note that the UDDS test was included for all three types of testing (i.e., chassis dynamometer, engine dynamometer, and on-road). The freeway/steady state cycles included the HHDDT cruise and the HHDDT-short or (HHDDT-S) cycle (which is a high-speed cruise schedule), and the steady state ramped mode cycle (RMC). The engine dynamometer version of the UDDS for each engine was developed from the engine operation recorded during the chassis dynamometer UDDS cycle. The engine dynamometer test cycles for the other CARB HHDDT tests were based on cycles that had been developed in previous programs.[1] The on-road test route was mostly freeway driving and went from University of California at Riverside's (UCRs) College of Engineering-Center for Environmental Research and Technology (CE-CERT) facility to Hesperia, CA from Hesperia, CA to Indio, CA, and then from Indio, CA returning to the CE-CERT facility. Cold start (CS) UDDS and FTP tests were also conducted for the chassis dynamometer and engine dynamometer testing, respectively. Testing included engine activity and concurrent emission measurements with a portable emissions measurement system (PEMS) and UCR's mobile emissions laboratory (MEL), with the exception of the on-road testing, where only PEMS were used.

Table ES-1 Summarized test cycles

Test method	Urban Cycles	Freeway Cycles
Initial Chassis01	Cold Start (CS)-UDDS, UDDS, HHDDT Transient	HHDDT Cruise 55, HHDDT Cruise 65
Engine	CS-FTP, FTP, eUDDS, HHDDT Transient	HHDDT Cruise 55, HHDDT Cruise 65, RMC
On-Road	UDDS	Riverside to Hesperia, Hesperia to Indio, Indio to Riverside
Final Chassis02	CS-UDDS, UDDS, HHDDT Transient	HHDDT Cruise 55, HHDDT Cruise 65

1. NOx and Other Emission Results

NOx emissions over different UDDS cycles are presented in Figures ES-1 on a g/bhp-hr basis. The results are based on the MEL measurements, which represent full laboratory measurements, for the dynamometer testing, and PEMS measurements for the on-road testing.

In general, results for the urban drive cycles were higher than those for the freeway driving conditions, which can be attributed to lower SCR operating temperatures throughout the cycle that reduce the effectiveness of the SCR in reducing engine out NOx. Over different urban cycles, NOx emissions for the Manufacturer A truck ranged from 0.28 to 0.91 g/bhp-hr. Similarly, NOx emissions for the Manufacturer B truck ranged from 0.16 to 1.05 g/bhp-hr. The highest emissions were found during

[1] Clark, N.N., M. Gautam, M., W.S. Wayne, D. Lyons, W. F. Zhen, C. Bedick, R.J. Atkinson, and D.L. McKain. 2007a. Creation of the "Heavy Heavy-Duty Diesel Engine Test Schedule" for representative Measurement of Heavy-Duty Engine Emissions, CRC Report No. ACES-1, CRC Website at crcao.org, July.

the CS-UDDS and regular UDDS on the chassis dynamometer for the Manufacturer A truck (0.72 to 0.91 g/bhp-hr), and during the CS-UDDS, CS-FTP, and engine dynamometer transient cycles for the Manufacturer B truck (0.68 to 1.05). The lowest emissions for urban cycles were found during the engine dynamometer UDDS (eUDDS) and FTP cycles for the Manufacturer A truck (approximately 0.3 g/bhp-hr) and during the on-road UDDS and initial chassis dynamometer transient cycles for the Manufacturer B truck (approximately 0.2 g/bhp-hr). FTP and RMC cycles are regulatory cycles for HDDE certification. NOx emissions for weighted FTP (1/7×Cold_FTP +6/7×Hot_FTP) cycle were above the certification level of 0.20 g/bhp-hr for both engines, with values of 0.34 and 0.45 g/bhp-hr for the Manufacturer A and Manufacturer B engines, respectively.

The results for the cruise/RMC tests were generally lower than those for the urban cycles. For the Manufacturer A truck, the cruise results were on the order of 0.10 g/bhp-hr, while the high-speed cruise results were 0.30 g/bhp-hr or less. For the Manufacturer B truck, the cruise and high speed cruise results were on the order of 0.30 g/bhp-hr or less. The average RMC results for both engines were comparable to or below the 0.20 g/bhp-hr NOx standard. The on-road testing results were higher for the both trucks, ranging from 0.22 to 0.50 g/bhp-hr for the Manufacturer A truck and from 0.35 to 0.49 g/bhp-hr for the Manufacturer B truck, with the highest emissions for the Hesperia to Indio test route for the Manufacturer A truck and for the Riverside to Hesperia test route for the Manufacturer B truck. Note that the Riverside to Hesperia test route is primarily uphill driving that puts a higher load on the engine, which could cause the higher emissions for that test route. While the Hesperia to Indio route includes considerable downhill driving, where the load on the engine is relatively low, which could be contributing to the higher emissions for that test route segment on a g/bhp-hr basis.

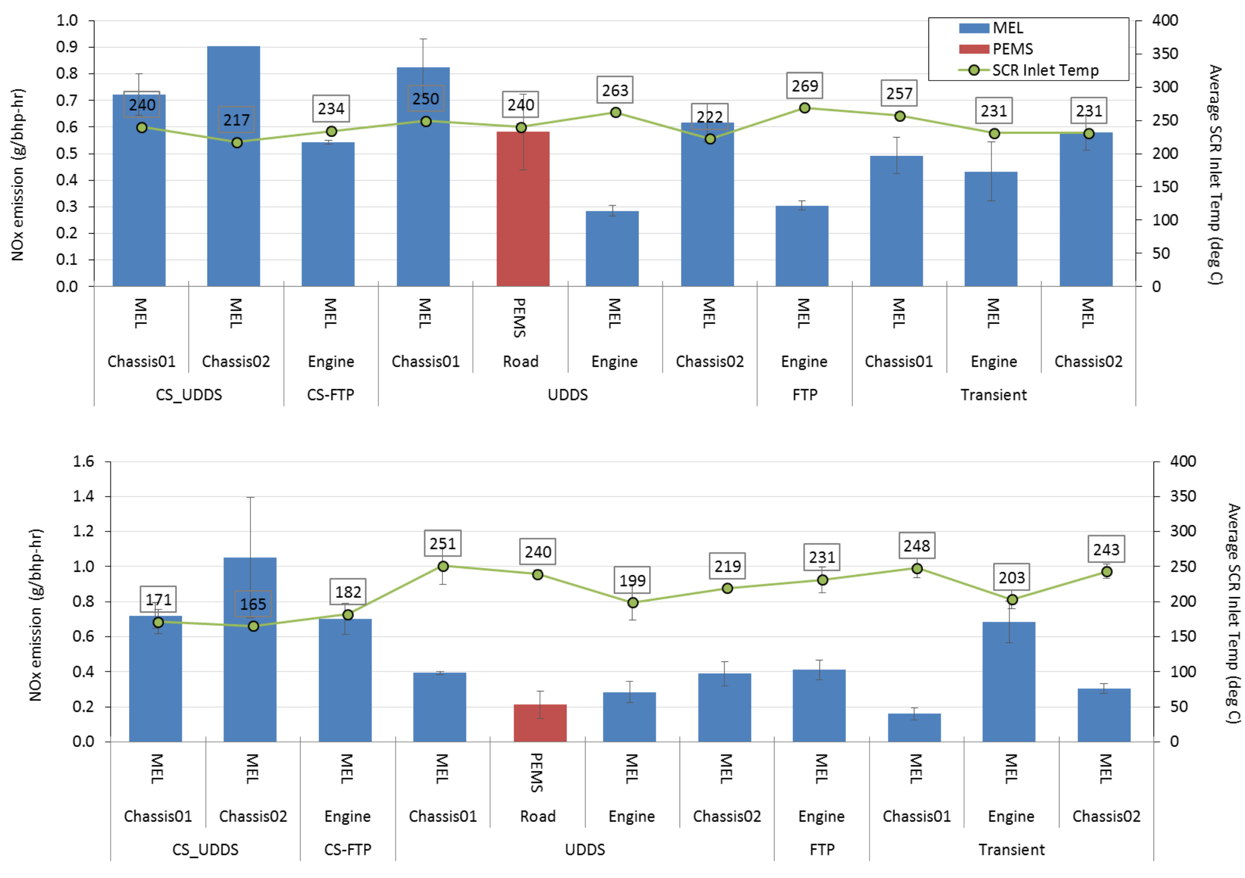


Figure ES-1 Average NOx Emissions on a g/bhp-hr basis for the urban cycles for the Manufacturer A Truck (top) and the Manufacturer B Truck (bottom)

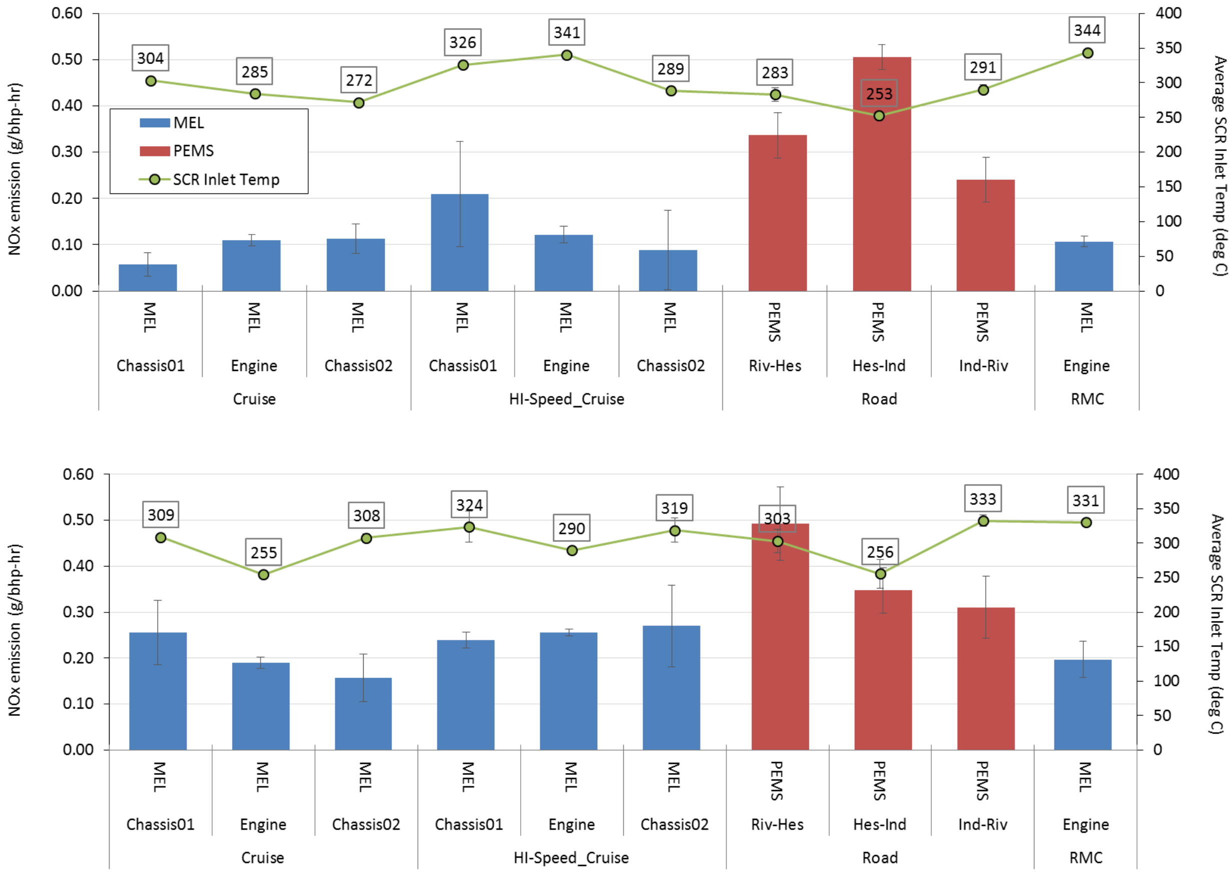


Figure ES-2 Average NO$_x$ Emissions on a g/bhp-hr Basis for the Freeway and RMC cycles for the Manufacturer A Truck (top) and the Manufacturer B Truck (bottom)

In comparing the results for the different test cycles between the different testing conditions (i.e., chassis dynamometer, on-road, and engine dynamometer), the results showed mixed trends, depending on the vehicle and test cycle for the urban driving cycles. The Manufacturer A truck for the UDDS showed the highest emissions for the chassis dynamometer testing, followed by the on-road testing, with the lowest UDDS emissions for the engine dynamometer testing. Discussions with Manufacturer A suggested that the engine could have been operating in a cold start mode during the engine dynamometer testing due in part to an absence of vehicle dashboard cluster communication, which potentially caused the engine to operate with retarded fuel injection timing. This explanation needs to be further evaluated; however, with a deeper investigation of the emission control related ECU parameters along with engine laboratory test conditions.

The Manufacturer B truck also showed the highest NOx emissions during the UDDS cycles on the chassis dynamometer, with comparable results for the on-road and engine dynamometer UDDS cycles. For the Manufacturer B truck/engine, the higher emissions for the chassis dynamometer were attributed to lower SCR temperatures and corresponding lower SCR NOx reduction efficiencies. Unfortunately, the fuel injection timing was not recorded from the engine from Manufacturer B, so we were unable to identify if its fuel injection timing behaved similarly as the engine from Manufacturer A. Interestingly, for Manufacturer B, the transient test results showed higher emissions for the engine dynamometer testing compared to the chassis dynamometer tests, which could be attributed to the lower SCR temperatures for the engine dynamometer tests.

The freeway/RMC testing results were more consistent in comparing between the chassis and engine dynamometer and on-road testing. Both trucks showed relatively comparable emissions for a given test cycle between the different testing conditions (i.e., chassis dynamometer, on-road, and engine dynamometer), except for the hi-speed cruise for the Manufacturer A truck and the cruise for the Manufacturer B truck. The on-road testing results were higher for the both trucks, compared with the cruise and hi-speed cruise cycles for the chassis dynamometer and engine dynamometer testing. Overall, it is suggested that additional investigations should be conducted to better understand the differences between engine dynamometer, chassis dynamometer, and on-road testing.

SCR temperature is an important measure of how effectively the SCR can remove NOx emissions, with temperatures above 250°C generally needed for the SCR to reach its full effectiveness. For Manufacturer A, most of the hot start cycles had average SCR inlet temperatures above 250°C, except for the UDDS cycle for the final chassis dynamometer tests, on-road UDDS and the transient cycles for the engine dynamometer and the final chassis dynamometer tests. For Manufacturer B, only the hot start UDDS cycles of the initial chassis dynamometer had average SCR temperatures above 250°C, with a range of 199 to 248°C for the other hot start urban cycles. While the average SCR temperatures for different urban cycles were often above 250°C, SCR temperatures would still vary for different parts of the cycle, which did lead to differences in NOx emissions between the different types of driving and testing methods that were used in this study. The average SCR inlet temperatures were at or above 250°C for the Cruise, HHDDT-S cycles, on-road driving cycles, and RMC cycles for both vehicles. Note that for the cruise cycles, not only were the average SCR temperature >250°C, but also a majority of the operation through the full cycle was above >250°C, which led to lower NOx emissions for the cruise cycles. The average SCR inlet temperatures for the cold start cycles were lower than those for the hot start cycles with a range from 217 to 240°C for Manufacturer A and from 165 to 182°C for Manufacturer B.

The efficiency of the SCR system in removing NOx was another important characteristic in understanding the different between different tests and different test methods. The cycle average SCR efficiencies for the Manufacturer A and Manufacturer B trucks ranged from 68 to 98%. For the Manufacture A truck, the SCR efficiencies for the cruise and hi-speed cruise cycles were higher than those for the urban driving cycles. For the Manufacturer B truck, the SCR efficiencies for the cruise and hi-speed cruise cycles were comparable to those for the urban driving cycles. The SCR efficiencies were found to be a function of the SCR inlet temperature for both vehicles. For inlet SCR temperatures higher than 250°C, the SCR conversion efficiencies remained consistently high (>80%). At temperatures below 250°C, the SCR efficiencies were generally lower, although this varied from cycle to cycle. The SCR efficiencies were also found to vary as a function of engine load, especially for the Manufacturer B truck. The highest SCR efficiencies (>90%) were observed between 30 to 60% load for the Manufacturer A truck and between 10 to 40% load for the Manufacturer B truck.

Other emissions

PM, CO and THC mass emissions were low for most of the test cycles. Average PM emissions were below 0.01 g/bhp-hr for both vehicles and nearly all tests. On a g/bhp-hr basis, CO emissions were up to 1.76 g/bhp-hr for the urban cycles, but were lower for the highway cycles, with all being below 0.13 g/bhp-hr. This is considerably below the 15.5 g/bhp-hr standard. THC emissions were higher for the urban test cycles, where all tests were below 0.046 g/bhp-hr, than the cruise/highway conditions, where all tests were below 0.007 g/bhp-hr. The highest THC emissions were seen for the cold start tests, including the CS_UDDS and CS_FTP.

2. NTE and MAW Analyses

The on-road NOx emissions results were evaluated based on the standard NTE criteria, which include various exclusions, such as operation where the power and torque are below 30% of maximum and where the aftertreatment temperature is below 250°C, and a requirement that the event duration is at least 30 seconds in durations. Additional analyses were also conducted where the criteria were modified to only exclude operation where the power and torque are below 10% of maximum. The results using the modified criteria were similar to those for the standard criteria, and they are discussed in greater detail in the main report. For 2010 and newer trucks, the passing criteria for the NTE test is that at least 90% of time-weighted NTE pass events should be below a threshold 0.45 g/bhp-hr for NOx, based on 1.5 times the certification standard + 0.15 g/bhp-hr (for a PEMS accuracy margin). NTE analyses were conducted separately for the triplicate tests over the three main on-road driving segments, including the Riverside to Hesperia, Hesperia to Indio, and Indio to Riverside routes, as the different routes were not necessarily conducted as a continuous sequence over the course of a single day.

The NTE analysis results are summarized in Table ES-2, including the number of valid NTE events and passing NTE events, the percentage of the total trip time in the NTE zone and in valid NTEs, and the percentage of total trip NOx emitted in the NTE zone and during valid NTE events. Over the test routes, the percentage of activity in the NTE zone ranged from 21.9 to 65.4% for the Manufacturer A truck and from 28.2 to 62.5% for the Manufacturer B truck. A smaller percentage of the activity also met the criteria for a valid NTE event, i.e., including requirements for having a duration of at least 30 seconds and an aftertreatment temperature > 250°C, ranging from 4.0 to 51.1% for the Manufacturer A truck and from 9.5 to 50.2% for the Manufacturer B truck. These activity fractions are higher than those that have been observed by CARB during its testing over the same routes, where NTE zone operation represented approximately 16% of operation and valid NTE events represented approximately 9% of operation. Note the CARB routes were longer comparing with our study due to the distance between El Monte to Riverside, where relatively few NTE events are generated. Over all routes, the Manufacturer A truck passed the NTE criteria for 7 of 9 tests, while the Manufacturer B truck passed for only 3 of 9 tests. Over the full test routes, a majority of the NOx was generated under operating conditions in the NTE zone (from 28.7 to 90.5% of NOx for the two trucks), while a much lower percentage of NOx was generated under conditions that met all the criteria for a valid NTE event (from 2.9 to 79.9% of NOx for the two trucks). It should be noted that percentage of valid test time and the percentage of NOx generated during valid NTE events is much higher than that found in the manufacturer-run the Heavy-duty In-Use Compliance (HDUIC) program, where studies of 2010-2014 model year data have indicated only 4.9% of operation represents valid NTE events and only 5.7% of NOx is generated in valid NTE events.[2] This could be due to a wider range of operating conditions that are covered in the HDUIC program, where test routes are less prone to generate large numbers of NTE events.

[2] Bartolome, C., Wang, L., Cheung, H., Lemieux, S., Heroy-Rogalski, K. and Robertson, W., 2018. Toward Full Duty Cycle Control: In-Use Emissions Tools For Going Beyond The NTE. Presentation at 28th CRC Real World Emissions Workshop, Garden Grove, CA, March.

Table ES-2 Summarized NTE analysis

Route	Route ID	All event		Pass event		Pass/Fail Ratio		NTE zone			Valid NTE event	
Manufacturer A truck												
		Numbers	Duration	Numbers	Duration			Activity %	NOx %	NOx (g/bhp-hr)	Activity %	NOx %
Riv-Hes	1	17	1470	15	1346	0.92	Pass	53.3	77.2	0.30	39.3	36.8
	2	7	656	7	656	1.00	Pass	35.8	35.0	0.18	18.0	21.7
	3	13	1494	12	1456	0.97	Pass	65.4	58.8	0.16	51.1	32.6
Hes-Ind	1	19	1234	14	1024	0.83	Fail	34.2	66.4	0.45	17.2	28.1
	2	4	281	4	281	1.00	Pass	21.9	28.7	0.33	4.0	2.9
	3	11	646	10	573	0.89	Fail	28.9	53.6	0.39	9.5	15.3
Ind-Riv	1	27	2707	26	2677	0.99	Pass	57.9	63.1	0.16	44.3	26.9
	2	18	2665	17	2532	0.95	Pass	51.9	77.0	0.26	40.3	22.7
	3	22	2390	22	2390	1.00	Pass	60.6	77.5	0.17	42.3	30.9
Manufacturer B truck												
Route	Route ID	All event		Pass event		Pass/Fail Ratio		NTE zone			Valid NTE event	
		Numbers	Duration	Numbers	Duration			Activity %	NOx %	NOx (g/bhp-hr)	Activity %	NOx %
Riv-Hes	1	14	1558	5	825	0.53	Fail	49.9	74.0	0.45	37.3	57.3
	2	17	1694	6	371	0.22	Fail	61.0	82.6	0.47	49.1	74.4
	3	8	891	3	420	0.47	Fail	44.4	59.7	0.38	14.1	12.0
Hes-Ind	1	9	520	7	360	0.69	Fail	28.2	48.1	0.36	9.5	24.4
	2	23	1379	16	923	0.67	Fail	38.2	82.7	0.33	18.3	52.2
	3	15	1048	14	955	0.91	Pass	35.7	68.3	0.27	16.0	46.2
Ind-Riv	1	25	2705	23	2509	0.93	Pass	62.5	90.5	0.26	50.2	79.9
	2	11	1197	9	1115	0.93	Pass	46.5	58.9	0.33	24.7	33.4
	3	20	2516	17	2235	0.89	Fail	50.7	88.0	0.27	38.3	69.0

Figure ES-3 shows NOx emissions for different operating conditions, including over the full trip, for operation in the NTE zone, for passing NTE events, for failing NTE events, and for operation outside the NTE zone. Average emissions for passing NTE events ranged from 0.09 to 0.24 g/bhp-hr for the Manufacturer A truck and from 0.29 to 0.41 g/bhp-hr for the Manufacturer B truck, while failing NTE events ranged from 0.71 to 1.12 g/bhp-hr and 0.72 to 0.83 g/bhp-hr, respectively, for the two trucks. NOx emissions for operation outside the NTE zone were significantly higher compared to those in the NTE zone for both vehicles. NOx emission rates during passing NTE events were lower than those for overall activity in the NTE zone and for the whole trip for the Manufacturer A truck. NOx emission rates for passing NTE events were comparable to those of overall activity in the NTE zone, but were lower than the values for the whole trip for the Manufacturer B truck.

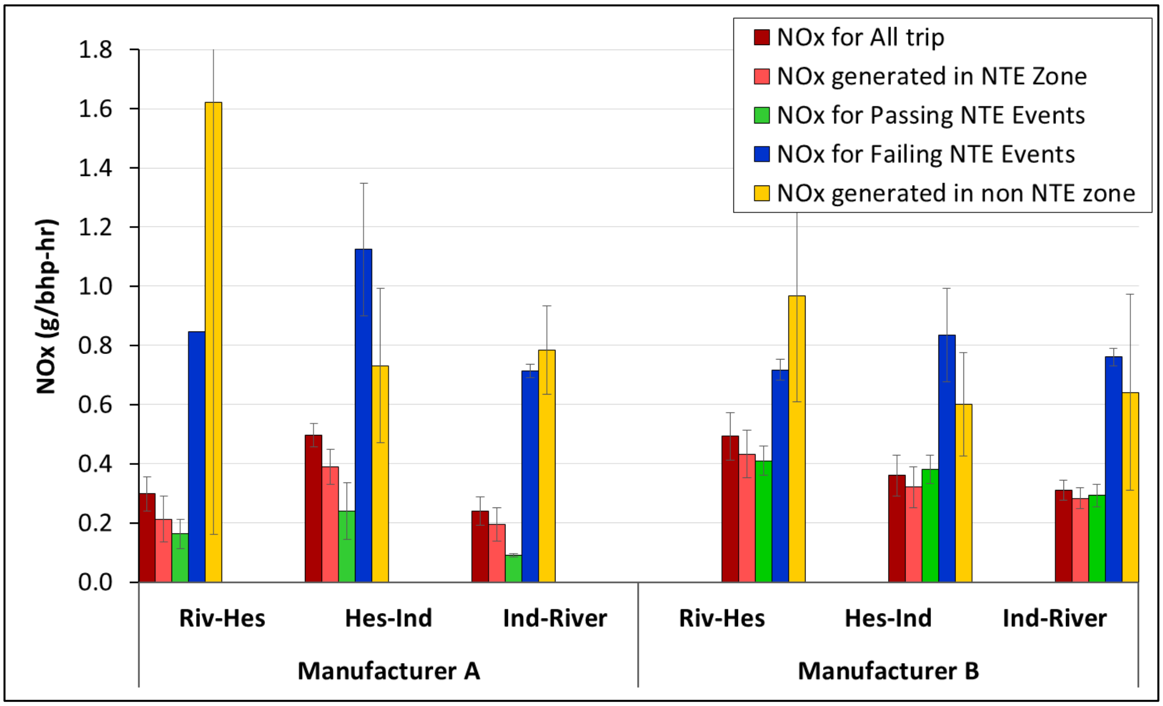


Figure ES-3 NOx emission rates of NTE zone and valid NTE events

The moving averaging window (MAW) method defines a continuous series of windows based on the amount of work done by the engine when it is certified on an engine dynamometer. In this case, that work is based on the results from the FTP engine dynamometer tests. For valid windows, average power is required to be at least 10% of max engine power, and at least 50% of the windows should be valid for a given test run to be considered valid. The MAW method also does not include an exclusion requiring the aftertreatment temperatures to be above 250˚C. For emissions, the pass fail criteria for the MAW method is that 90% of the windows should have emissions less than 1.5 times the certification limit, which is generally termed the conformity factor (CF). The measurement allowance that is used to account for potential PEMS inaccuracies for the NTE method is not included in the MAW method. As such, the MAW method is more stringent in terms of have less data exclusion, as well as a lower emissions threshold.

The results of the MAW analyses are shown in Table ES-3. The activity analysis of this study showed a significant improvement of the amount of data that that met the MAW criteria compared with that for the NTE criteria. The emissions were found to fail the MAW test for a majority of the routes. Only two tests for the Riverside to Hesperia route passed for the Manufacturer A truck, while the Manufacturer B truck failed the MAW test for all the tests on each test route. The fraction of operation passing the MAW criteria for the Manufacturer A truck ranged from 36 to 93%, with most tests higher than 63%. The fraction of operation passing the MAW criteria for the Manufacturer B truck ranged from 6 to 80%, with half of tests below 36%. Since the NTE criteria excludes test data where the SCR temperature is lower than 250˚C, as NOx conversion efficiencies are relatively low at these lower temperatures, the MAW method was evaluated with this temperature criteria added for the Manufacturer A truck. Although the overall pass rate didn’t change by eliminating data points with low SCR efficiency operation, the fraction of operation below the emission threshold of 1.5 times the certification standard increased 14% for the Hesperia to Indio route and 10% for the Indio to Riverside route. The coverage of valid windows decreased after applying the temperature criteria, but the overall coverage was still higher than 59%. Other studies of 2010-2014 model year data from the HDIUC program have indicated that 60.1% of operation would represent valid MAW windows, which would in turn represent 61.6% of the NOx generated.

Figure ES-4 shows that NOx emissions for failing windows were significantly higher than those of passing windows. Average emissions for pass MAW windows ranged from 0.08 to 0.15 g/bhp-h for the Manufacturer A truck and from 0.20 to 0.24 g/bhp-h for the Manufacturer B truck, while failing MAW windows ranged from 0.54 to 0.70 g/bhp-h and 0.44 to 0.52 g/bhp-h, respectively, for the two trucks.

Table ES-3 Summarized MAW analysis

Manufacturer A									
Route	Route ID	All MAW Windows	Window Avg g/bhp-hr	MAW Valid (%) Windows	Window Avg g/bhp-hr	CF Total	CF <= 1.5	CF <=1.5 (%)	Pass/Fail
CERT-Hes	1	2984	0.244	100	Valid Test	2984	2367	79.3	Fail
	2	2911	0.186	100	Valid Test	2911	2667	91.6	Pass
	3	2287	0.210	100	Valid Test	2287	2125	92.9	Pass
Hes-Ind	1	6801	0.497	100	Valid Test	6801	2432	35.8	Fail
	2	6563	0.505	100	Valid Test	6563	2735	41.7	Fail
	3	6316	0.482	100	Valid Test	6316	2305	36.5	Fail
Ind-CERT	1	5597	0.244	100	Valid Test	5597	3582	64.0	Fail
	2	6048	0.260	100	Valid Test	6048	3814	63.1	Fail
	3	5088	0.179	100	Valid Test	5088	3721	73.1	Fail
Manufacturer B									
Route	Route ID	All MAW Windows	Window Avg Nox g/bhp-hr	MAW Valid (%) Windows	Window Avg Nox g/bhp-hr	CF Total	CF <= 1.5	CF <=1.5 (%)	Pass/Fail
CERT-Hes	1	3311	0.471	100	Valid Test	3311	206	6.2	Fail
	2	2383	0.489	100	Valid Test	2383	385	16.2	Fail
	3	2343	0.379	100	Valid Test	2343	604	25.8	Fail
Hes-Ind	1	4994	0.588	100	Valid Test	4994	1091	21.8	Fail
	2	7062	0.351	100	Valid Test	7062	2553	36.2	Fail
	3	6049	0.310	100	Valid Test	6049	3306	54.7	Fail
Ind-CERT	1	4922	0.234	100	Valid Test	4626	3436	74.3	Fail
	2	4395	0.363	100	Valid Test	4395	1937	44.1	Fail
	3	5802	0.248	100	Valid Test	5802	4638	79.9	Fail

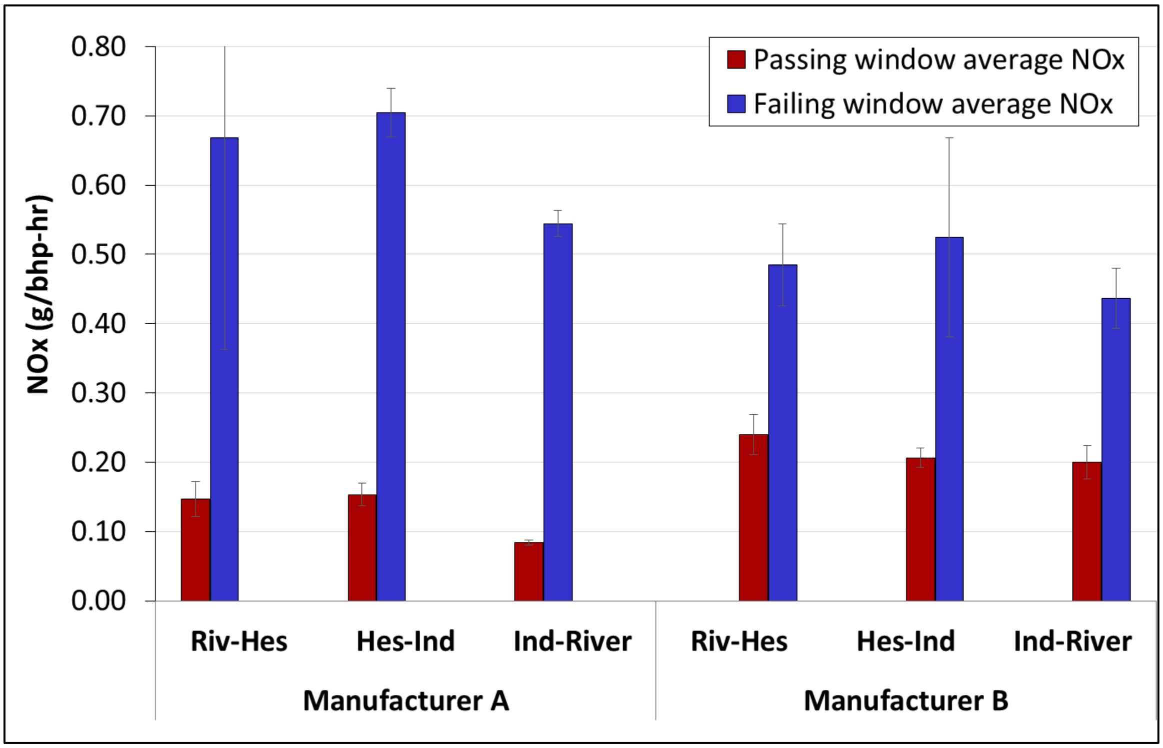


Figure ES-4 Average NOx emission rates for passing and failing MAW windows

Conclusions, Implications, and Recommendations

Although this study was limited to only two vehicles/engines, when combined information from the open literature, the results indicate that in-use NOx emissions can be above the 0.2 g/bhp-hr level for a wide range of different driving conditions. Differences between different types of laboratory and on-road testing could be attributed to factors that impact engine out NOx and the SCR catalyst temperatures and performance, which in turn contribute to differences in tailpipe NOx emissions. The results suggest that further investigation is warranted to better understand differences between NOx emissions obtained during certification testing and real-world operation, and how gaps can be narrowed moving into the future.

It is likely that a combination of tightened certification limits, expanded certification testing, and expanded in-use compliance procedures will be needed to provide greater control of in-use NOx emissions. In terms of certification procedures, a reduction of the certification standard to 0.02 g/bhp-hr is currently under consideration by CARB, and studies are on-going to evaluate techniques, such as advanced aftertreatment and improved thermal management, that could be used to achieve such levels. Additional provisions will also likely be needed to reduce emissions for vocations that operate under low load conditions, where the SCR efficiency can be much lower. This could include the development of additional certification cycles that would provide for better control of NOx emissions under low load conditions.

The current procedures for in-use compliance testing also have limitations, in that the exclusion criteria for NTE testing eliminates a large fraction of in-use operation. In our study, the fraction of in-use operation that met the criteria for a valid NTE event represented between 4.0 to 51.1%, representing between 2.9 and 79.9% of the total NOx for the on-road testing. Other studies of the manufacturer-run the Heavy-duty In-Use Compliance (HDUIC) program, have indicated only 4.9% of operation represents valid NTE events and only 5.7% of NOx is generated in valid NTE events. The MAW methodology, currently being used in Europe, provided improved coverage of in-use operation, and could provide a better methodology for capturing NOx emissions under a full range of operating conditions. In our study, all of the NOx generated from the on-road testing met the criteria for valid MAW windows, compared to 4.0 to 51.1% of operation for the NTE method. Other analysis has indicated that the percentage of test time in valid MAW windows for the HDUIC would improve to 60.1% using the MAW method, which would represent 61.6% of the generated NOx. It is also possible that greater control of in-use NOx emissions could be obtained by placing a greater emphasis on in-use compliance testing through the use of sensors, such as those incorporated as part of the on-board diagnostic (OBD) system, that could be utilized to track emissions performance on a continuous basis.

1 Introduction

The State of California has a number of regions that are out of compliance with national air quality standards for both ozone and particulate matter (PM) emissions. Although considerable progress has been made in reducing the contributions of vehicle emissions to the emissions inventory and in improving air quality, further reductions in oxides of nitrogen (NOx) emissions are still needed to achieve future air quality goals. Heavy-duty diesel vehicles (HDDVs) and heavy-duty diesel engines (HDDEs) are the largest sources of NOx emissions, and as such have been the source of a number of regulations. The implementation of new emissions beginning in 2010 for new HDDEs were designed to provide 90 percent reductions in NOx emissions, which have generally been met by selective catalytic reduction (SCR) aftertreatment control strategies in combination with other engine design changes. California also has an In-use Truck and Bus regulation designed to accelerate fleet turnover such that by the 2023 nearly all trucks operating in California will have engines complying with the 2010 emissions standards.

In order to achieve air quality goals, it is important that the levels of reductions anticipated with the implementation of more stringent emissions standards can be achieved during typical operating conditions on the road. Currently, HDD engines are certified to meet emission standards before the engines are integrated into a vehicle chassis for commercial use. HDDE certification tests in the United States (U.S.) are conducted on an engine-dynamometer over the Federal Test Procedure (FTP) cycle that was developed to be representative of real-world HDDV driving patterns. For 2004 and later model year engines, an additional supplementary emissions test (SET) cycle was added to the certification procedure for engines meeting U.S. EPA standards. This is due in part to the wide range of applications that a particular engine might be used for, and the expense/complexity of testing vehicles from a wide range of applications on a heavy-duty chassis dynamometer. HDDEs integrated into a vehicle chassis for commercial use also need to comply with in-use HDDV not-to-exceed (NTE) emission limits and testing requirements (U.S. Environmental Protection Agency [EPA]). The NTE regulations include requirements intended to ensure that in-use HDDV emissions are controlled over a wide range of speed and load, especially during sustained high load, steady-state operations. The NTE requires monitoring of emissions under in-use conditions for a subset of engines sold in different engine families for a give engine manufacturer.

While significant steps have been taken to reduce NOx emissions from HDDVs, it is still uncertain how effective these changes have been in reducing in-use NOx emissions. The NTE regulations, were designed primarily to prevent off-cycle emissions from high-speed high-load line-haul operation on freeways, but a substantial fraction of vehicle activity and NOx emissions are not subjected to in-use emission limits, especially under low-speed, low-load, stop-and-go conditions. Additionally, chassis dynamometer and on-road testing are showing smaller reductions in NOx emissions than would be expected based on the emissions standards. This includes recent studies that have shown that NOx emissions measured from 2010 in-use HDDV on chassis-dynamometers over the Urban Dynamometer Driving Schedule (UDDS) cycle are substantially higher than the certification standard of 0.2 g/bhp-hr NOx (Miller et al., 2013; Quiros et al., 2017; California Air Resources Board [CARB], 2018; Thiruvengadam et al., 2015). Although the conditions for the UDDS on a chassis dynamometer do not replicate the FTP on an engine dynamometer, the UDDS is designed to be compared to the FTP engine-dynamometer cycle and the engine torque and RPM values experienced over the UDDS cycle are similar to the torque and RPM values from the FTP engine dynamometer cycle.

Given the importance of achieving actual NOx emissions over the road, it is important to investigate and understand the differences between certification and in-use emission rates and to understand the factors contributing to these differences and discrepancies. For this program, two 2010-compliant HDDV engines equipped with diesel particulate filter (DPF) and selective catalytic reduction (SCR) technologies were evaluated using an engine-dynamometer, a chassis-dynamometer, and on-road. This study included an evaluation of the emissions as well as the activity differences between the different methods. Testing was conducted over a number of different cycles or driving conductions to evaluate a wide range of engine and vehicle operations. Test data collected from all measurement methods were analyzed and compared with each other. The differences between the different test methods were also evaluated in terms of the theoretical principles, purposes, and characteristics of the different methods. Based on findings from this study, the effectiveness of current HDDE certification procedures and HDDV in-use compliance procedures was assessed and possible enhancements or alternatives to those procedures were evaluated.

1.1 Objective

The objective of this study is to better understand the differences between NOx emission measurements under certification conditions on an engine dynamometer in comparison with in-use testing conditions on a chassis dynamometer or on-road using the same engines. The study evaluated these differences via direct experimental measurements as well as a review of the literature and theory behind the different methods of emissions measurements. The results from this study were used to evaluate the effectiveness of current HDDE certification and HDDV in-use compliance procedures for controlling in-use NOx emissions from HDDVs and to suggest possible changes to these procedures that could facilitate meeting ambient air quality standards for ozone and PM in California.

2 Literature Review

Background information of HDDE engine certification and in-use HDDV NTE compliance test procedures including theoretical principles, purposes, and characteristics of engine-dynamometer testing over the FTP cycle, chassis-dynamometer testing over the UDDS cycle, and on-road PEMS testing was gathered. Comparison analyses of the engine activities and emissions measured over the FTP, UDDS, and in-use on-road driving cycles were conducted, and fundamental differences between the cycles in terms of engine torque, RPM, and NOx emissions were identified.

To establish a background for conducting the engines vs. chassis vs. on-road testing and understanding the results, the University of California at Riverside's (UCR's) Bourns College of Engineering-Center for Environmental Research and Technology (CE-CERT) evaluated information related to each of the different methods of testing. This included looking at the different testing types, their methodologies, the general principles on which the methods are based, and how the different methods were developed. As part of this investigation, UCR evaluated some data from previous/on-going programs to look at parameters that affect the formation of NOx emissions, including aftertreatment temperatures as well as differences in engine load, torque, and engine RPM.

The literature review also investigated in-use compliance programs, including those using Not-to-Exceed (NTE) criteria and Moving Average Window (MAW) criteria. This included information about the implementation of these programs. An important element of these analyses was to evaluate what portions of different cycles would meet the requirements for being subject to different in-use compliance standards. Such comparisons included investigations of portions of the cycle that might meet the criteria for one compliance test, such as the MAW, but not the other, such as the NTE. This provided information as to whether the exclusion zones for the NTE or MAW represent major areas where excess NOx may be emitted. This also provided information on how effective these in-use compliance measures are in controlling in-use emissions.

As part of this background evaluation, we also tried to identify vehicles with substantially higher in-use emission rates from on-road PEMS or chassis dynamometer testing over cycles similar to the heavy duty UDDS, as compared to certification testing results.

This section summarizes the results and findings from the literature review, and provides recommendations that were used in the design of the other phases of this study.

2.1 Review of Testing Methodologies

2.1.1 Engine Dynamometer Testing

The primary method for measuring the emissions and performance of heavy-duty and other engines over the years has been an engine dynamometer. The dynamometer is used to apply a load to the engine and measure its power output. A dynamometer consists of an absorption (or absorber/driver) unit, a means for measuring torque and rotational speed, and a coupling between the engine and the dynamometer.

Engine dynamometers are the cornerstone of the certification process, particularly for heavy-duty and off-road engines. Unlike passenger cars and passenger trucks, heavy-duty on-road and off-road engines can be used in a variety of applications and vocations. Additionally, for on-road heavy-duty applications, there are a more limited number of chassis dynamometers that can be used for testing such trucks and other vehicles. These among other factors have kept the certification testing process tied to engine dynamometer testing for this category.

Several different types of tests are conducted on engine dynamometer, including the following general procedures:

1. Engine mapping: the engine is tested under a load (i.e. inertia or brake loading) while sweeping continuously through the engine revolutions per minute (RPM) from a near idle to a top speed.
2. Steady state: The engine is held at a specified series of RPM and engine load points while emissions measurements are collected for a given period of time.
3. Transient test: The engine power and speed are varied throughout the test cycle. Transient tests are usually done with alternating current (AC) or direct current (DC) dynamometers. A variety of transient test cycles have been developed that are applied in different applications, as discussed further below.

The types of test cycles utilized in the certification process differ between different engine categories. On-highway engines have been tested over the Federal Test Procedure (FTP) for certification. The FTP was designed to represent different types of driving that is found for heavy-duty trucks and buses in urban streets and highways, with various parts of the cycle representing different types of driving in Los Angeles (LA) and New York (NY). Although the heavy-duty FTP is not broken up into Bags or phases like the light-duty FTP, there are four unique segments or phases within the cycle. These include (1) the New York Non Freeway (NYNF) phase typical of light urban traffic with frequent stops and starts, (2) the Los Angeles Non Freeway (LANF) phase typical of crowded urban traffic with few stops, (3) the Los Angeles Freeway (LAFY) phase simulating crowded expressway traffic in Los Angeles, followed by (4) a repetition of the first NYNF phase. The variation of normalized speed and torque as a function of time is shown in Figure 2-1.

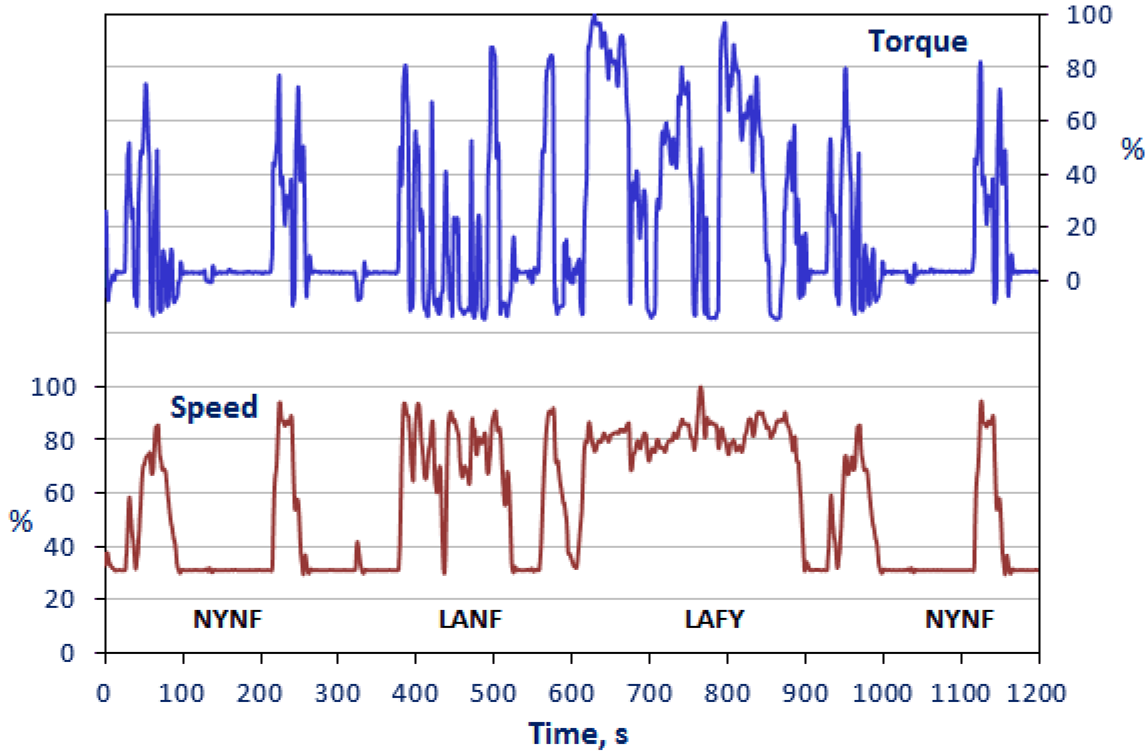


Figure 2-1. FTP Transient Cycle (source: Dieselnet)

The average load factor of the FTP cycle is roughly 20-25% of the maximum engine power available at a given engine speed (www.dieselnet.com). The equivalent average vehicle speed is about 30 km/h and the equivalent distance traveled is 10.3 km for a running time of 1200 s. Heavy-duty diesel engines tested on the hot FTP cycle produce medium to high exhaust gas temperatures. Generally, the temperature is at a medium level between 200 and 350°C, but there are hot sections with temperatures reaching as high as 450°C. It can also take on the order of 10 minutes to increase the SCR temperature up to 250°C over a cold-start FTP cycle.

The cycle is run as both a cold- and a hot-start test for certification testing. The cold start is typically run in the morning after the engine is soaked overnight. Following the cold start test, there is a 20-minute soak and then three hot start tests can be run consecutively with a 20 minute soak in between each test. For the purpose of engine certification, the emissions from the cold start and hot start FTPs are weighted by a factor of 1/7 for the cold start and 6/7 for the hot start tests, as described in 40 CFR §86.1342-90.

The certification test procedures were augmented in the late 1990s as part of the consent decree to incorporate a wider range of operating conditions. This included the addition of a Supplemental Emissions Test (SET), which was a multi-mode test covering a range of steady state operating conditions. The SET cycle was put in place for engines meeting U.S. EPA standards for 2004 and later emissions standards. Typically, one of two ramped mode cycles (RMC) are run to satisfy the SET requirement, although manufacturers also had the option of running a discrete mode cycle (DMC) through the 2009 model year. These cycles are described below.

The DMC SET is equivalent to the European Stationary Cycle (ESC). The SET is a 13-mode steady-state engine dynamometer test. The DMC SET cycle was an alternative option to the RMC for engines up through the 2009 model year. The set points for the DMC SET cycle are provided in Table 2-1, as described in 40 CFR §86.1363-2007.

Table 2-1. Discrete Mode SET Cycle

Mode No.	Engine speed[1]	Percent load[2]	Weighting factors	Mode length (minutes)[3]
1	Warm Idle		0.15	4
2	A	100	0.08	2
3	B	50	0.10	2
4	B	75	0.10	2
5	A	50	0.05	2
6	A	75	0.05	2
7	A	25	0.05	2
8	B	100	0.09	2
9	B	25	0.10	2
10	C	100	0.08	2
11	C	25	0.05	2
12	C	75	0.05	2
13	C	50	0.05	2

[1] Speed terms are defined in 40 CFR part 1065.
[2] The percent torque is relative to the maximum torque at the commanded test speed.
[3] Upon Administrator approval, the manufacturer may use other mode lengths.

There is a specific RMC that is used for heavy-duty engines up to the 2009 model year. This 2007 RMC includes the same operating modes and weightings as the DMC test, but the order is different and there is a defined transition between modes. Manufacturers were able to use either the 2007 RMC or DMC SET through the 2009 model year. The 2007 RMC SET cycle is provided in

Table 2-2, as described in 40 CFR §86.1362-2007, with speeds A, B and C defined as specified in 40 CFR 1065.

Table 2-2. Ramped Modal Cycle for 2007-2009 Heavy-Duty Engines

RMC mode	Time in mode (seconds)	Engine speed[1,2]	Torque (percent)[2,3]
1a Steady-state	170	Warm Idle	0
1b Transition	20	Linear Transition	Linear Transition
2a Steady-state	170	A	100
2b Transition	20	A	Linear Transition
3a Steady-state	102	A	25
3b Transition	20	A	Linear Transition
4a Steady-state	100	A	75
4b Transition	20	A	Linear Transition
5a Steady-state	103	A	50
5b Transition	20	Linear Transition	Linear Transition
6a Steady-state	194	B	100
6b Transition	20	B	Linear Transition
7a Steady-state	219	B	25
7b Transition	20	B	Linear Transition
8a Steady-state	220	B	75
8b Transition	20	B	Linear Transition
9a Steady-state	219	B	50
9b Transition	20	Linear Transition	Linear Transition
10a Steady-state	171	C	100
10b Transition	20	C	Linear Transition
11a Steady-state	102	C	25
11b Transition	20	C	Linear Transition
12a Steady-state	100	C	75
12b Transition	20	C	Linear Transition
13a Steady-state	102	C	50
13b Transition	20	Linear Transition	Linear Transition
14 Steady-state	168	Warm Idle	0

[1] Speed terms are defined in 40 CFR part 1065.
[2] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the speed or torque setting of the current mode to the speed or torque setting of the next mode.
[3] The percent torque is relative to maximum torque at the commanded engine speed.

For 2010 and later model year heavy-duty engines, manufacturers must use the 2010 ramped mode SET. It is similar to the 2007 ramped mode SET with the exception that the order in which the modes are run is the same as for the DMC SET and ESC cycles. The 2010 RMC SET cycle is provided in Table 2-3, as described in 40 CFR §86.1362-2007, with speeds A, B and C defined as specified in 40 CFR 1065.

Table 2-3. Ramped Modal Cycle for 2010 and Newer Heavy-Duty Engines

RMC mode	Time in mode (seconds)	Engine speed [1,2]	Torque (percent) [2,3]
1a Steady-state	170	Warm Idle	0
1b Transition	20	Linear Transition	Linear Transition.
2a Steady-state	173	A	100
2b Transition	20	Linear Transition	Linear Transition.
3a Steady-state	219	B	50
3b Transition	20	B	Linear Transition.
4a Steady-state	217	B	75
4b Transition	20	Linear Transition	Linear Transition.
5a Steady-state	103	A	50
5b Transition	20	A	Linear Transition.
6a Steady-state	100	A	75
6b Transition	20	A	Linear Transition.
7a Steady-state	103	A	25
7b Transition	20	Linear Transition	Linear Transition.
8a Steady-state	194	B	100
8b Transition	20	B	Linear Transition.
9a Steady-state	218	B	25
9b Transition	20	Linear Transition	Linear Transition.
10a Steady-state	171	C	100
10b Transition	20	C	Linear Transition.
11a Steady-state	102	C	25
11b Transition	20	C	Linear Transition.
12a Steady-state	100	C	75
12b Transition	20	C	Linear Transition.
13a Steady-state	102	C	50
13b Transition	20	Linear Transition	Linear Transition.
14 Steady-state	168	Warm Idle	0

[1] Speed terms are defined in 40 CFR part 1065.
[2] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the speed or torque setting of the current mode to the speed or torque setting of the next mode.
[3] The percent torque is relative to maximum torque at the commanded engine speed.

In addition to the regulatory cycles, a number of other representative cycles were developed as part of the Advanced Collaborative Emissions Study (ACES). For the ACES study, test cycles were developed to represent the four main modes of truck operation that are included in the Heavy Heavy-Duty Diesel Truck (HHDDT) Chassis Schedule, discussed below, including the Creep, Transient, Cruise, and High-Speed Cruise (HHDDT_S) modes (Clark et al., 2007a). These test cycles were developed by West Virginia University (WVU) based on based on engine control unit (ECU) data taken from trucks driven on a chassis dynamometer during the E-55/59 program, and are presented in Appendix B. The test cycles were developed by converting all of the available engine speed and torque data from the chassis dynamometer testing to percent engine speed and percent torque based on micro-trips within the chassis dynamometer cycles. The test cycles were then modified to ensure they performed properly on the engine dynamometer, including the addition of “closed rack” (zero fueling) operating points, and new regression criteria were developed for each mode using the data obtained during testing. These individual test cycle modes were then combined into a 16 hour test cycle that was used in the ACES diesel engine health effect studies (Clark et al., 2007b). The 16 hour test cycle include a roughly 50/50 time split between urban and rural driving, where the urban operation included transient, creep, and FTP modes and the rural driving included cruise and high-speed cruise modes.

2.1.2 Chassis Dynamometer Testing

For light-duty and medium-duty vehicles, chassis dynamometer testing is more commonly used for certification and emissions characterization. Chassis dynamometer are becoming increasingly more important in characterizing the emissions of heavy-duty vehicles, as it is important to understand how engines in vehicle chassis perform under typical driving conditions. Chassis dynamometers include a roll or rollers that the vehicle is positioned on during a simulated driving schedule. The dynamometer roll/rollers apply a load to the vehicle tires based on the type of driving that is being simulated and measure the power being delivered by the drive wheels.

The load applied to a vehicle on a chassis dynamometer is designed to simulate the forces that the vehicle needs to overcome when driving on the road. This includes forces due to tire rolling resistance and aerodynamic drag. Road grade can also be included if desired. These forces are a function of vehicle speed, drag coefficient, frontal area and tire rolling resistance coefficient, as shown in equation 1:

$$M\frac{dV}{dt} = \frac{1}{2}\rho A C_D V^2 + \mu M g cos(\theta) + M g sin(\theta) \qquad \text{(Equation 1)}$$

Where:

M = mass of vehicle in lbs

ρ = density of air in kg/m^3.

A = frontal area of vehicle in square feet, see Figure 2-2

C_D = aerodynamic drag coefficient (unitless). Typical values are presented in Table 2-4.

V = speed vehicle is traveling in mph.

μ = tire rolling resistance coefficient (unitless), as shown in Table 2-4.

g = acceleration due to gravity = 32.1740 ft/sec^2.

θ = angle of inclination of the road grade in degrees, which is often set to be zero for a flat road.

Table 2-4. Constants used in the Coastdown Calculation

Constant parameters for equation 1	
μ	0.007
C_D	0.75 for Truck 0.79 for Bus 0.80 for Refuse Truck

The road load coefficients that are actually utilized by the dynamometer to simulate these road load forces are developed via a quadratic equation. This quadratic equation is developed from data representing the amount of time that it take for a vehicle to decelerate from approximately 60 to 10 mph. The quadratic equation takes the form shown in equation 2, where v is the vehicle speed.

$$Y = C(v^2) + B(v) + A \qquad \text{(Equation 2)}$$

By assuming that the vehicle loading is defined based on equation 1, the amount of time it will take for a vehicle to coast down can be estimated by calculation. The calculation uses assumed values for C_D (0.75 [heavy-duty truck] 0.79 [bus] and 0.80 [refuse hauler] and the tire rolling resistance coefficient, along with the vehicle mass, and measurements of the vehicle’s front area.

The vehicle front area is calculated based on measurements, as shown in Figure 2-2, per SAE J1263 measurement recommendations. The calculated speed vs. time for a coast down based on this equation are then used to determine the A, B, C coefficients in equation 2 for the dyno operation parameters. This is currently the most widely used method to determine road load coefficients. This is the method typically utilized by both the UCR and WVU laboratories, as outlined in Miller et al. (2013). This approach is consistent and has proven very reliable for chassis testing of heavy duty vehicles for a number of years. It should be noted that as more advanced and aerodynamic designs for truck chassis are developed under programs such as the Smartway program, the values for C_D may need to be expanded to more accurately reflect potentially lower C_D values.

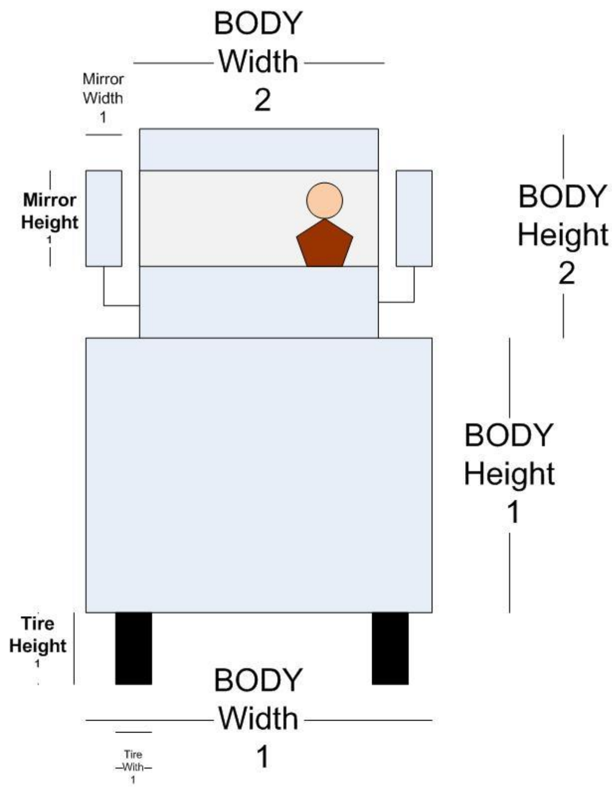


Figure 2-2. Vehicle frontal area dimensions method

Road load coefficients can be determined from tests where a vehicle is actually coasted down on an actual roadway. While in-use coastdowns provide a direct measure of a vehicles performance on an actual roadway, experience has shown that performing in-use coast downs is complicated and time consuming, and requires grades of less than 0.5% over miles of distance, average wind speeds < 10 mph ± 2.3 mph gusts and < 5 mph cross wind[3]. As such, performing in-use coastdowns in CA is often unreliable, as the wind is unpredictable and the grades on most roadways are not sufficiently flat for a long enough stretch of road.

[3] EPA Final rulemaking to establish greenhouse gas emissions standards and fuel efficiency standards for medium and heavy duty engines and vehicles, Office of Transportation and Air Quality, August 2011 (Page 3-7) and J1263 coast down procedure for fuel economy measurements

A variety of test cycles have been utilized to characterize various types of driving or typical operation for various types of vehicles, such as buses or refuse haulers. The discussion below provides a summary of some of the most common cycles. A more comprehensive overview of test cycles is provided in sources such as dieselnet,com.

UDDS Description

The heavy-duty vehicle Urban Dynamometer Driving Schedule (UDDS) is a cycle commonly used to represent transient urban driving on a chassis dynamometer. This cycle covers a distance of 5.55 miles with an average speed of 18.8 mph, sample time of 1061 seconds, and maximum speed of 58 mph. The speed/time trace for the UDDS is provided below in Figure 2-3.

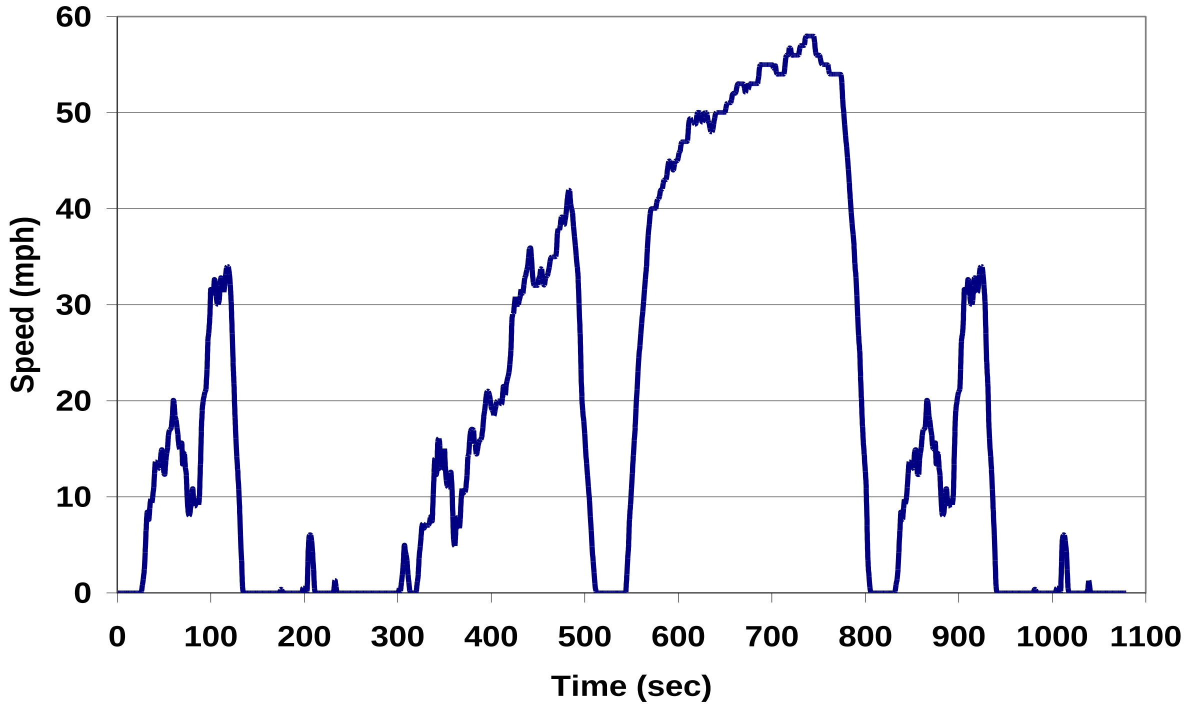


Figure 2-3. Speed vs time trace for the UDDS cycle

Central Business District (CBD)

The Central Business District (CBD) Cycle is a chassis dynamometer testing procedure for heavy-duty vehicles (*SAE J1376*). The CBD cycle represents a "sawtooth" driving pattern, which includes 14 repetitions of a basic cycle composed of idle, acceleration, cruise, and deceleration modes. The following are characteristic parameters of the cycle:

- Duration: 560 s
- Average speed: 20.23 km/h
- Maximum speed: 32.18 km/h (20 mph)
- Driving distance: 3.22 km
- Average acceleration: 0.89 m/s^2
- Maximum acceleration: 1.79 m/s^2

Vehicle speed over the duration of the CBD cycle is shown in Figure 2-4. This cycle is sometimes combined into a triple CBD to provide greater sampling time for the collection of PM filters and toxics for low emitting vehicles.

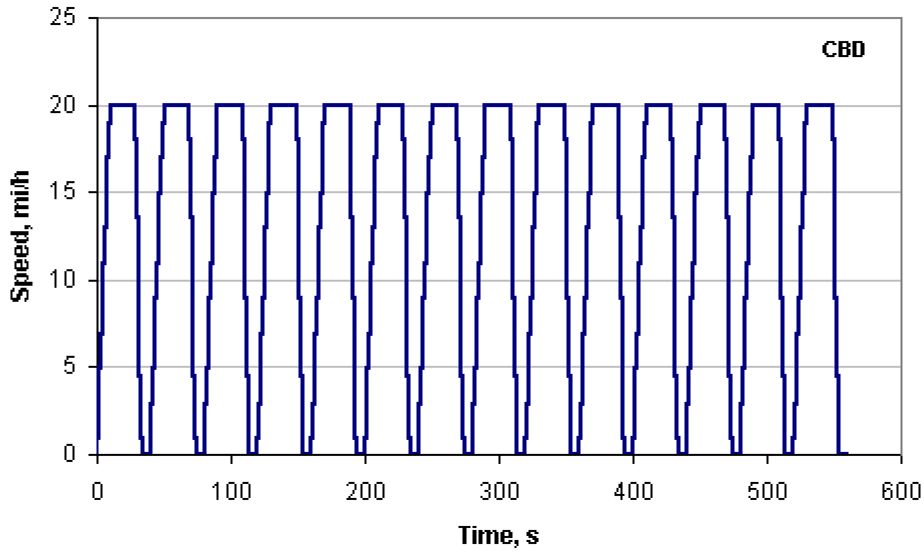


Figure 2-4. CBD Driving Cycle

California Air Resources Board – Heavy-Duty Diesel Truck Driving Cycles

The Heavy Heavy-Duty Diesel Truck (HHDDT) schedule was developed by CARB in conjunction with WVU. There are four main segments of the HHDDT cycle, including an idle, creep (Figure 2-5), transient (Figure 2-6), and cruise (Figure 2-7) (Gautam, et al. 2002). Subsequent to the development of the four main segments, an additional shorter high speed cruise cycle (HHDDT-S) was developed to characterize higher speed highway driving, as shown in Figure 2-8 (Clark et al., 2004). Some of the fundamental characteristics of these cycles are provided in Table 2-5.

Table 2-5. Description of Test Cycles

Schedule	Time (s)	Avg Speed (mph)	Distance (mi)	Description
HHDDT Idle	900	0	0	Idle of vehicle
HHDDT Creep	256	1.7	0.124	Stop and go modes (congestion)
HHDDT Transient	688	14.9	2.9	Local street driving
HHDDT Cruise	2083	39.9	23.1	Freeway driving
HHDDT-Short	760	49.9	10.5	High speed driving

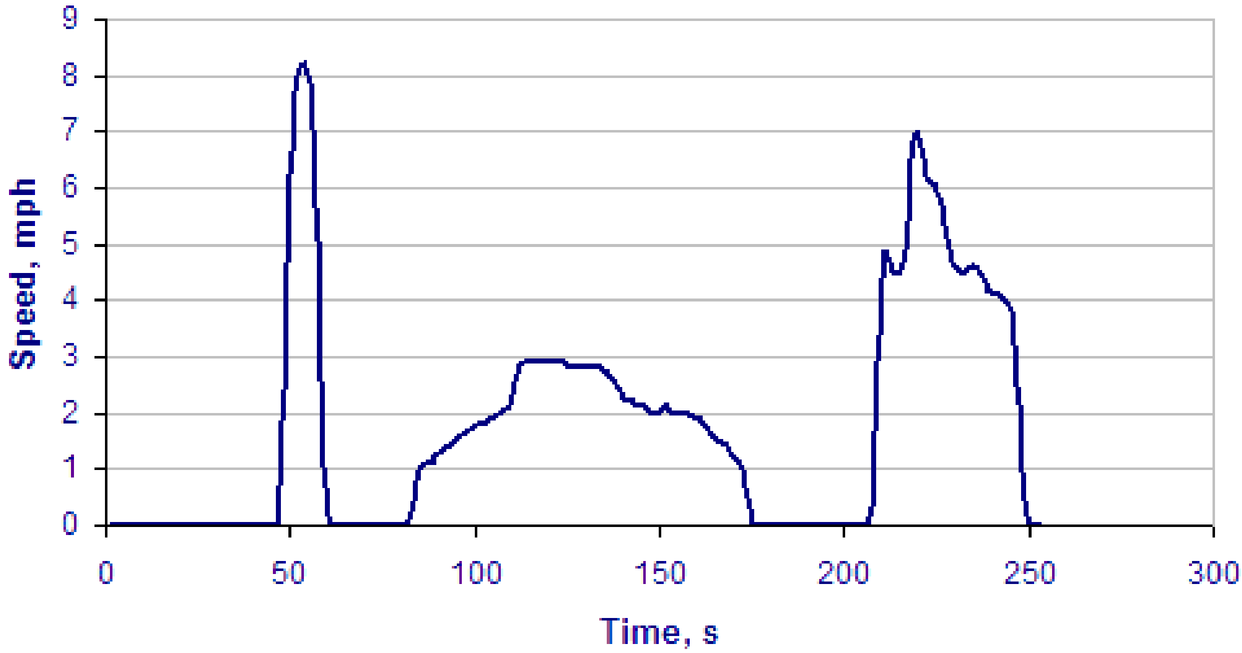


Figure 2-5. Speed/Time Trace for a HHDDT-Creep cycle for the chassis dynamometer.

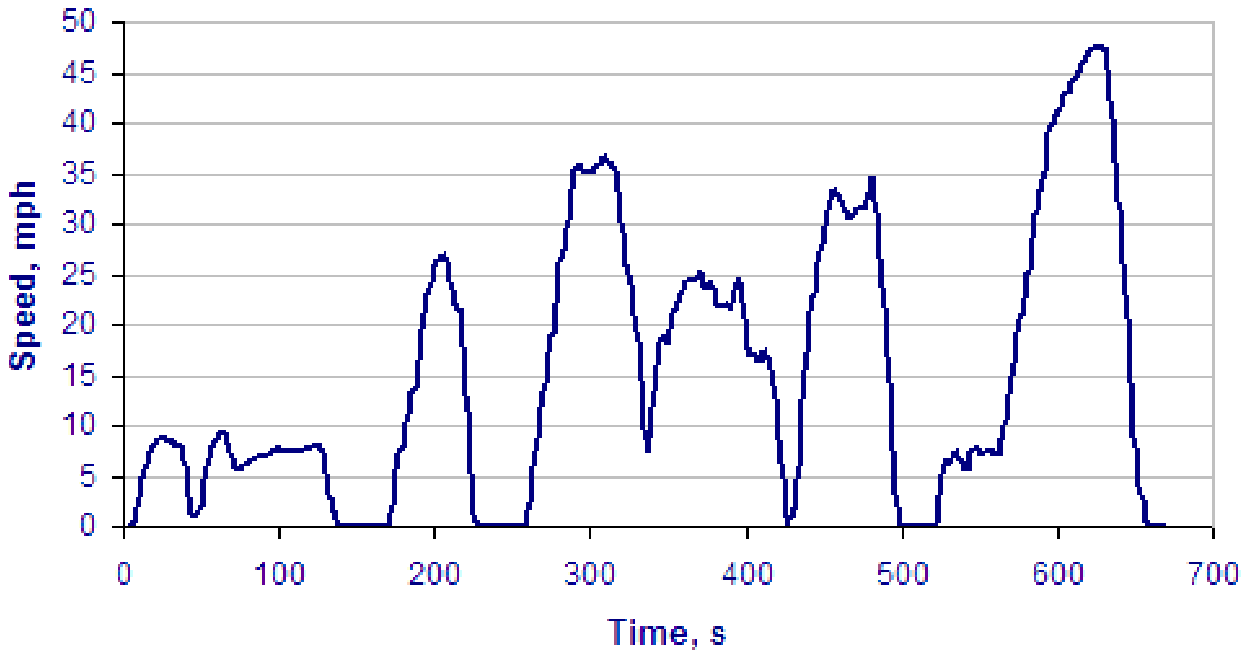


Figure 2-6. Speed/Time Trace for a HHDDT-Transit cycle for the chassis dynamometer.

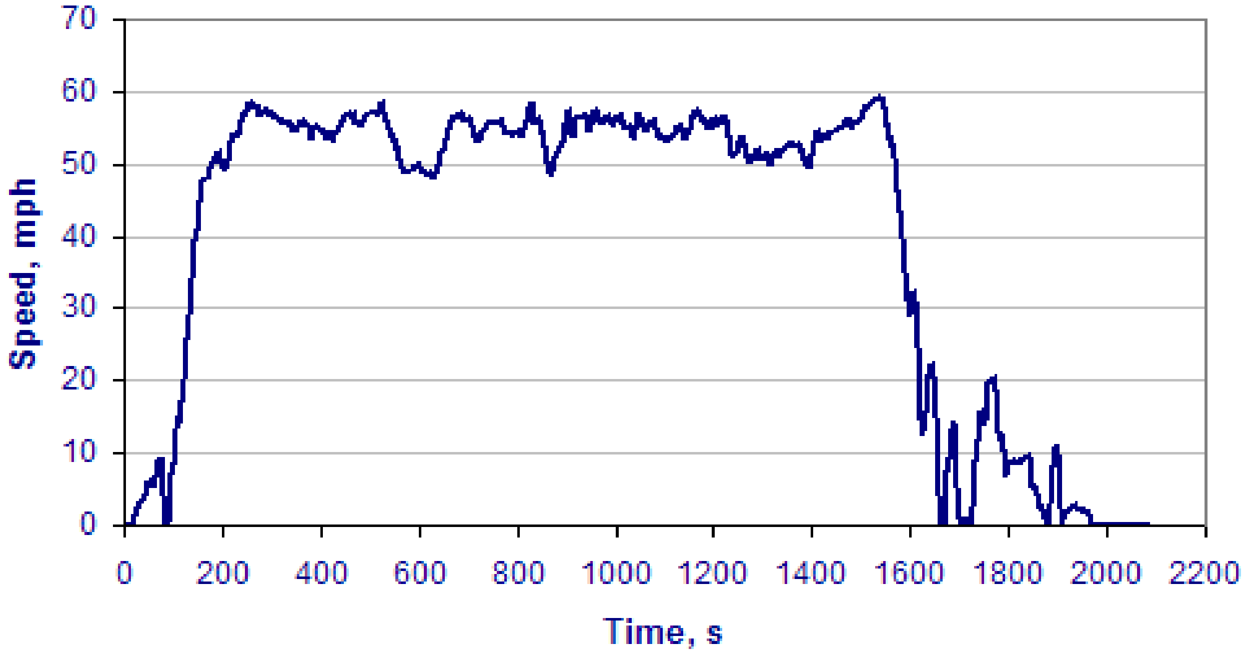


Figure 2-7. Speed/Time Trace for a HHDDT-Cruise cycle for the chassis dynamometer.

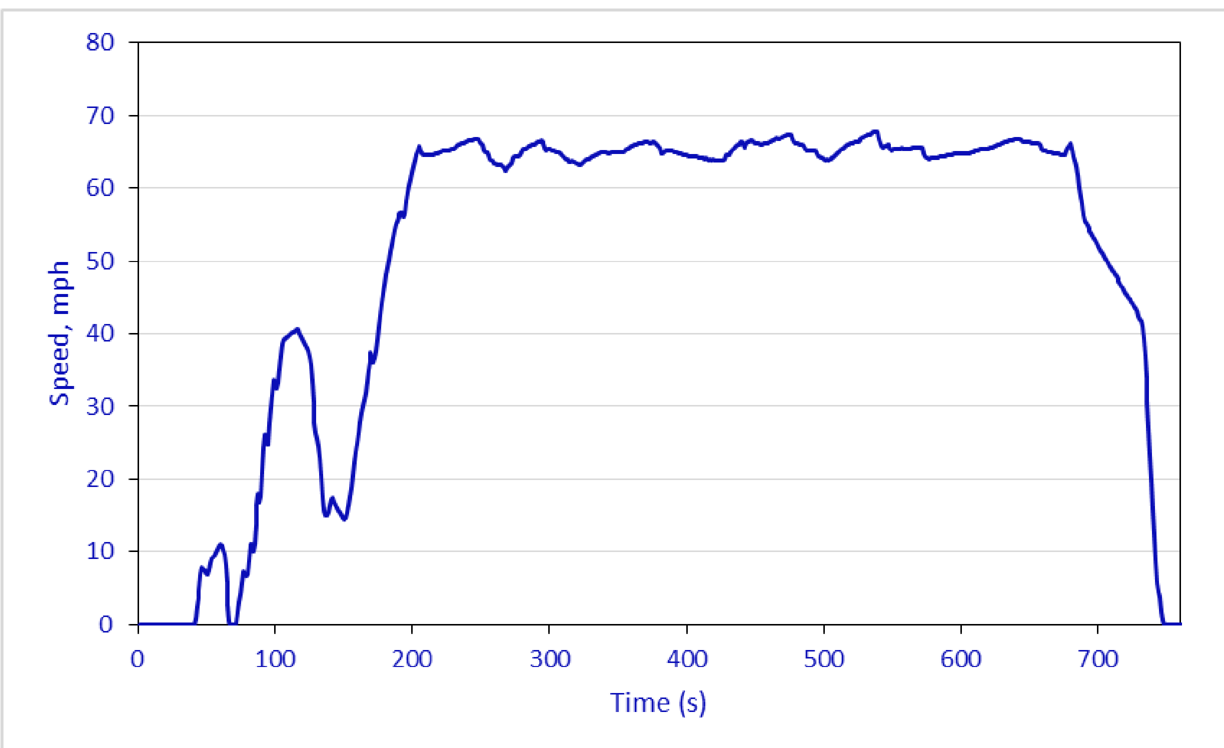


Figure 2-8. Speed/Time Trace for a HHDDT-hi speed cruise cycle for the chassis dynamometer.

Drayage Truck Port (DTP) cycles

The Drayage Truck Port (DTP) cycles were developed based on activity data collected at the Ports of Long Beach and Los Angeles (TIAX, 2011). These cycles include combinations of different driving conditions, which include queuing or on-dock operation, near-dock, local or regional operation, and freeway operation, which was broken down into 5 different phases, as shown in Table 2-6. Three different DPT cycles were developed based on these 5 different phases. These three cycles were designed to best represent near dock, local, and regional driving, as shown in Table 2-7 and Figure 2-9. All three cycles begin with phases 1 and 2 from Table 2-6, and then add in a third phase distinct to the specific operation. The near-dock (DTP-1) cycle is composed of phases 1, 2, and 3 from Table 2-6. The Local cycle (DTP-2) is composed of phases 1, 2, and 4. The Regional cycle (DPT-3) is composed of phases 1, 2, and 5. The preconditioning cycles for the different cycles are shown in Figure 2-10.

Table 2-6. Drayage Truck Port cycle by phases

Description	Phase #	Distance Mi	Ave Speed mph	Max Speed mph	Cycle length
Creep	1	0.0274	0.295	4.80	335
low speed transient	2	0.592	2.67	16.8	798
short high speed transient	3	4.99	9.39	40.6	1913
Long high speed transient	4	8.09	13.07	46.4	2229
High speed cruise	5	24.6	35.04	59.3	2528

Table 2-7. Drayage Truck Port cycle by mode and phases

Description	Distance mi	Ave Speed mph	Max Speed Mph	Mode 1	Mode 2	Mode 3
Near-dock PDT1	5.61	6.6	40.6	Creep	Low Speed Transient	Short High Speed Transient
Local PDT2	8.71	9.3	46.4	Creep	Low Speed Transient	Long High Speed Transient
Regional PDT3	27.3	23.2	59.3	Creep	Low Speed Transient	High Speed Cruise

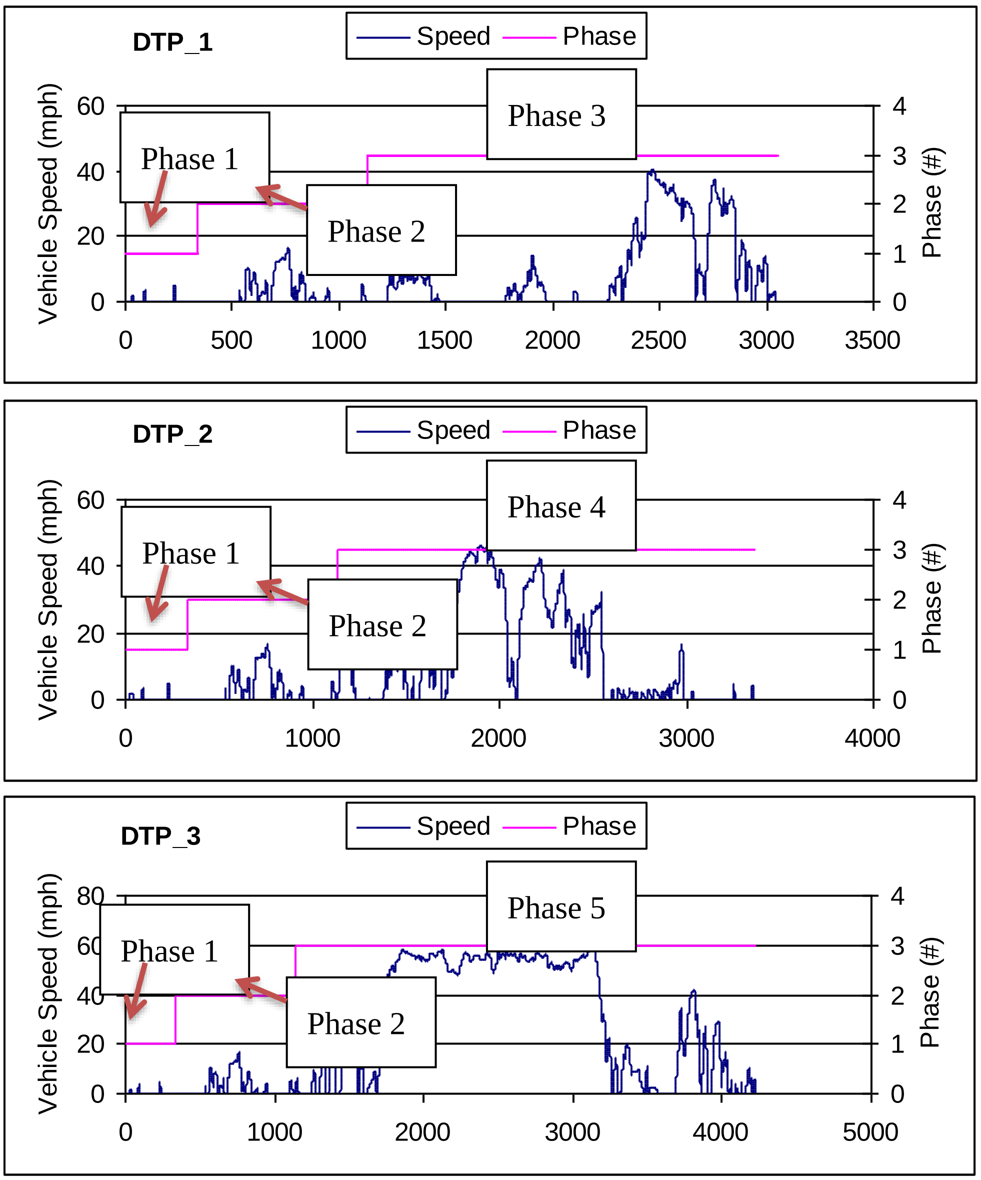


Figure 2-9. Drayage truck port cycle near dock, local, and regional.

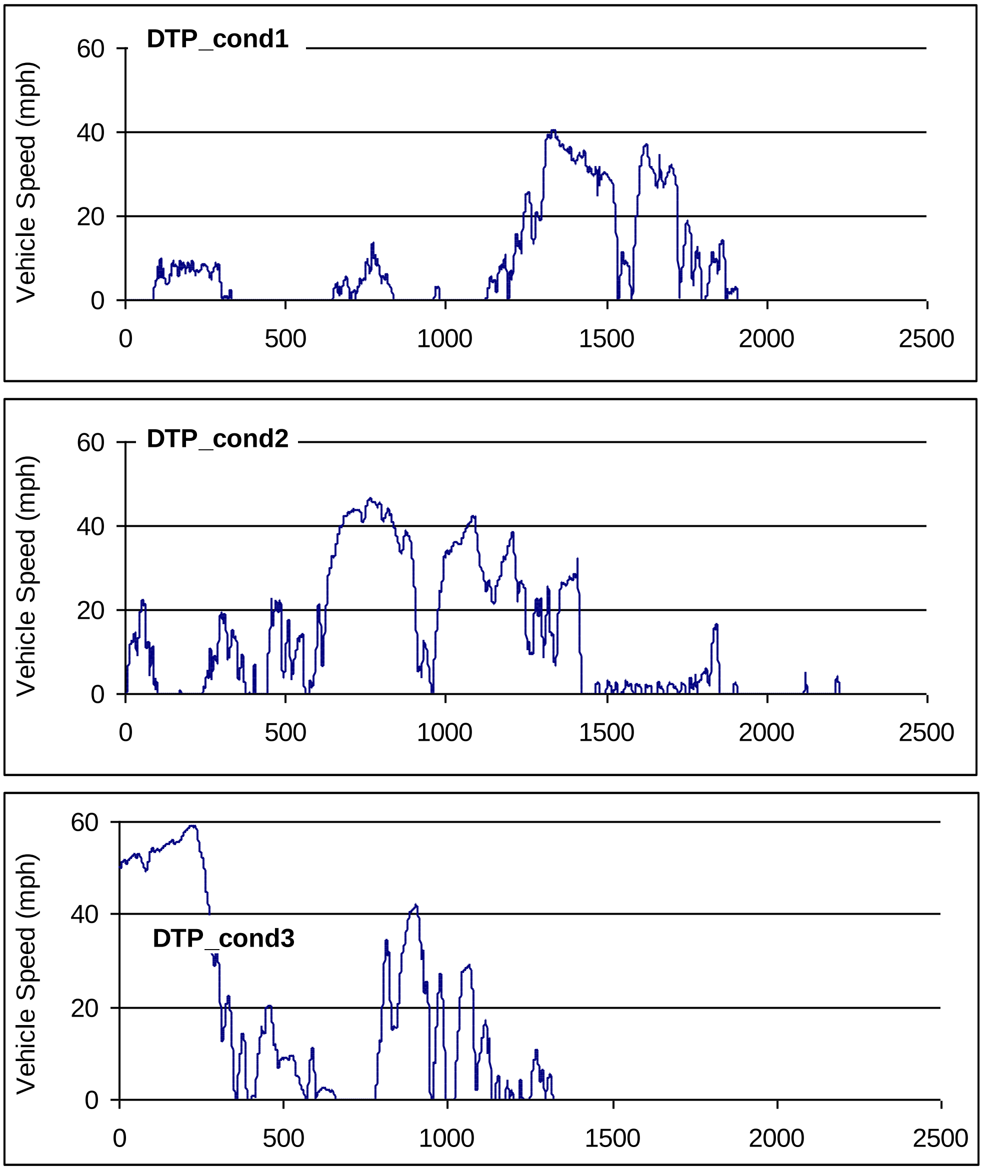


Figure 2-10. Drayage truck port cycle conditioning segments consisting of phase 3 parts

R*efuse Truck Cycles*

The William H. Martin (WHM) refuse truck cycle was created from data logged from sanitation trucks operating in Pennsylvania. The cycle consists of a transport segment (phase 1), a curbside pickup segment (phase 2), and a compaction segment (phase 3), see Figure 2-11. The initial 293 second segment of the cycle is a warm-up period where no emissions are collected. The transient phase starts at 293 seconds and stops at 830 seconds, the curbside starts at 830 seconds and ends at 1428 seconds and the final compaction cycle starts at 1500 seconds. The compaction portion of the cycle represents the final 250 seconds.

The compaction load is simulated by applying a predetermined torque to the drive axel while maintaining a fixed speed of 30 mph. Previous studies have used an engine load varying between

20 hp to 78 hp for the compaction load, as shown in the right hand side of Figure 2-11. To perform the compaction cycle the vehicle is accelerated up to 30 mph where no emissions are collected. Once steady state load conditions are achieved the emissions collection starts and then the varying load is applied. The emissions collection stops before the vehicle is decelerated back to zero speed.

Since, the compaction operation does not accumulate distance (miles) in the real-world, the emissions from the compaction cycle was represented in conjunction with the time speed trace by simply accumulating the emissions of both phases and dividing by the distance of the moving phases (1 and 2).

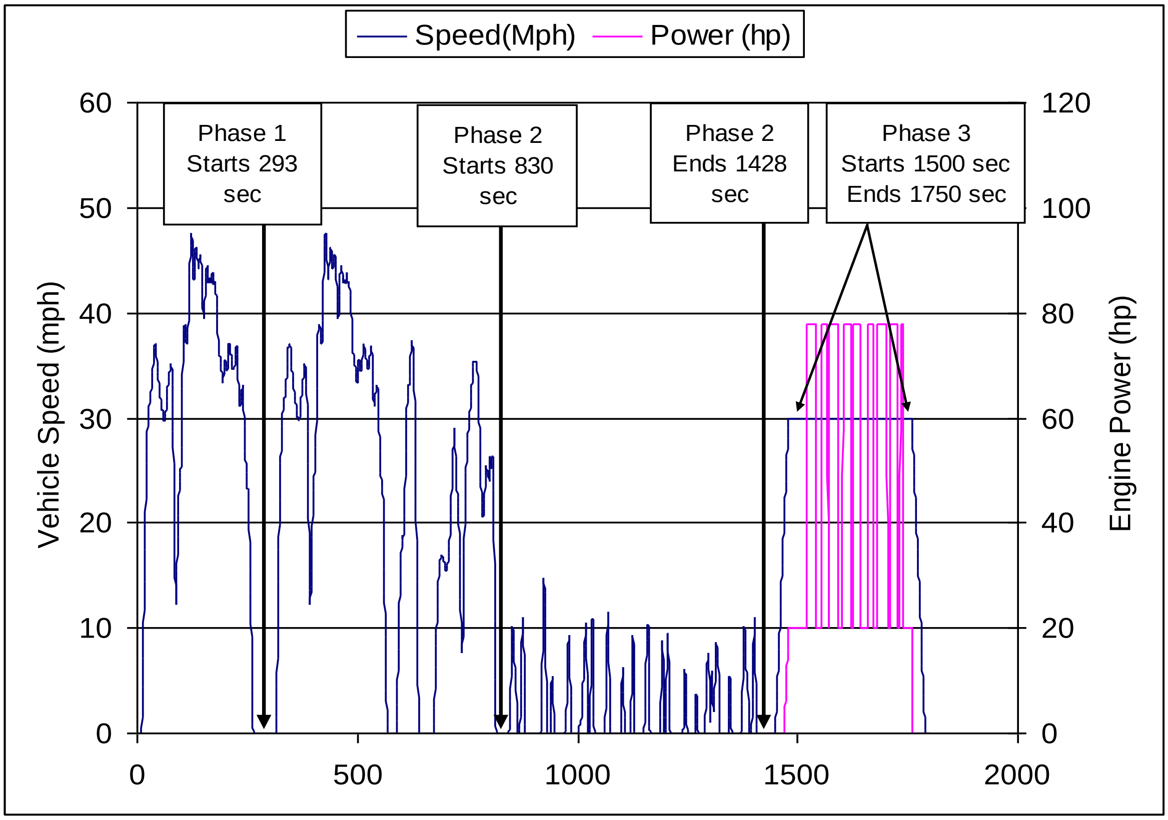


Figure 2-11. WHM Refuse Truck Cycle (WHM-RTC)

The AQMD refuse truck cycle (AQMD-RTC) is the same as the WHM-RTC in that the cycle consists of a refuse truck operation and the compaction operation, with the main difference being the length of time and arrangement of the individual modes (transport, curbside, and compaction). The duration of the AQMD-RTC transport and curbside is 2117 seconds, representing a distance of 4.3 miles. Figure 2-12 shows the vehicle speed vs. time trace for the AQMD refuse truck cycle. The curb side pick-up mode is representative of multiple short idle times with frequent stop-and-go operation. The cycle is characterized by frequent accelerations and decelerations. The frequent stop-and-go operation could lead to lower catalytic activity and higher mass tailpipe emissions rates.

A second cycle was developed to represent the compaction operation of a refuse hauler. Engine load information was obtained from the ECU during in-use compaction operation, in order to develop a representative chassis cycle to represent the compaction operation on the chassis dynamometer. The compaction cycle involved the operation of the vehicle at steady-state speed of 30 mph with an intermittent axle loading of 80 hp and 20 hp applied to simulate the auxiliary loading of the compaction system. The compaction cycle is 880 seconds long and covers an equivalent distance travelled of 6.8 miles. Figure 2-13 shows the vehicle speed vs. time trace and axle power loading of the refuse truck compaction cycle.

Since, the compaction operation does not accrue any driving miles in real-world, the emissions from the compaction cycle were represented on a time-specific basis. Further, in order to represent the distance-specific emissions of the refuse truck operation as a whole, the total mass of emissions from the compaction cycle are integrated and then combined with the emissions from the other phases.

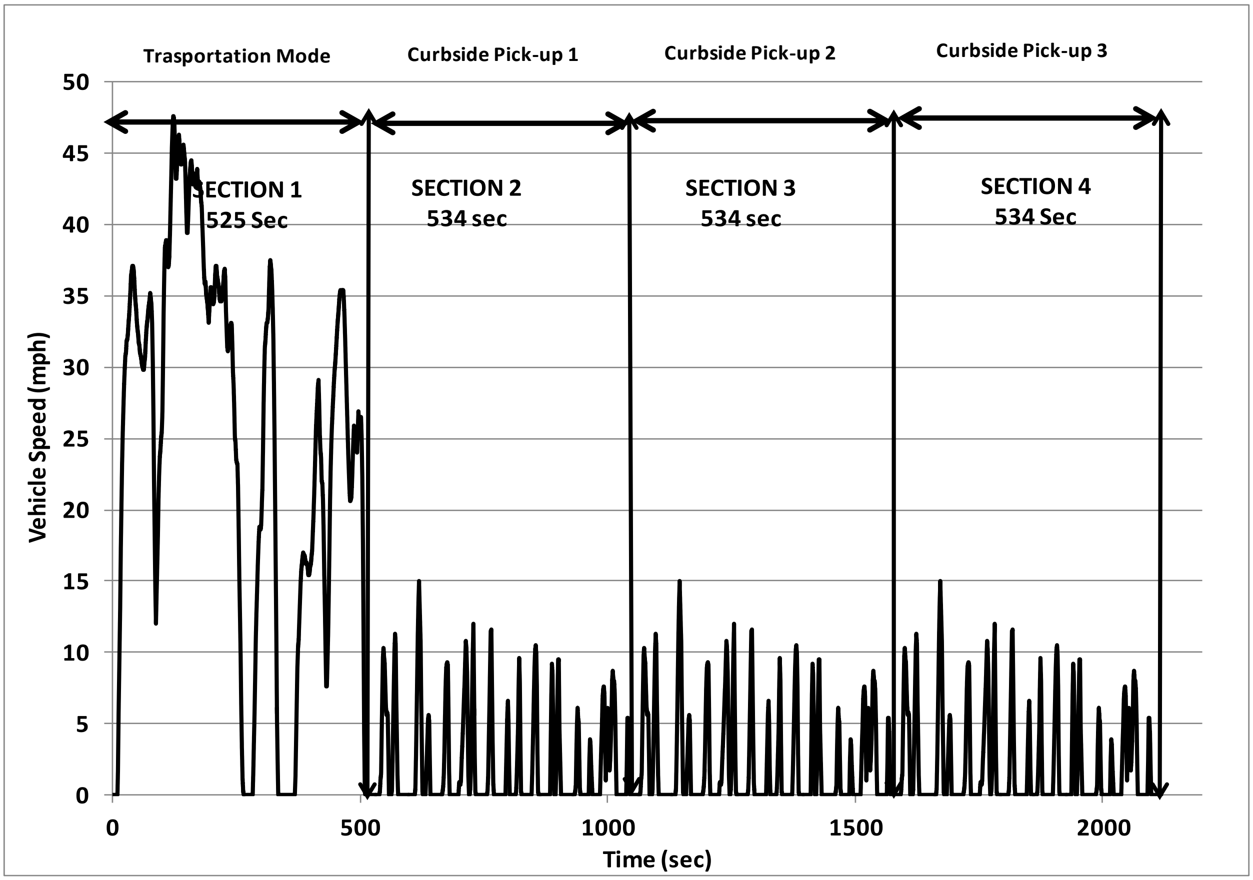


Figure 2-12. Speed trace for AQMD refuse truck driving cycle

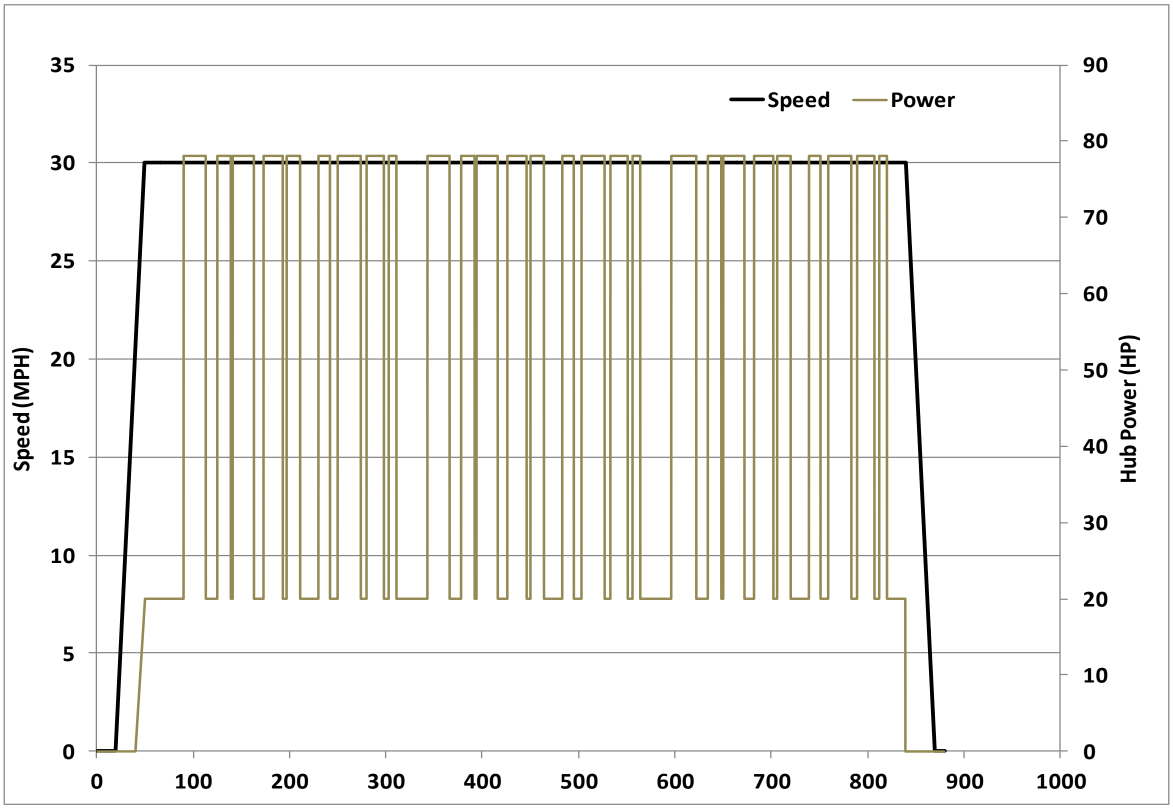


Figure 2-13. Speed trace for AQMD refuse truck compaction cycle

2.1.3 In-use Testing

It has long been known that dynamometer testing alone has been insufficient to characterize the emissions that are seen under the full range of conditions found under typical in-use driving conditions, or the full range of maintenance levels seen in the in-fleet. As early as the 1980s, tunnel studies had shown that true emission rates from vehicles were higher than the typical rates used in emissions inventory models. Remote sensing studies over the years have also shown that a portion of the fleet that are high emitters contribute disproportionately to the emissions inventory.

To better understand in-use emissions under a wide range of in-use driving conditions, portable emissions measurement systems (PEMS) have been developed. PEMS are designed to provide the capability of measuring emissions typically measured in the laboratory, but in a more compact package that can be installed in a vehicle or piece of equipment so that measurements can be made while the vehicle or piece of equipment is being operated. The PEMS technology has evolved considerably over the years. Early versions of PEMS include the ROVER, developed by Leo Breton at the U.S. EPA (Johnson, 2002), and the MEMS, developed by WVU (Gautam et al., 2001). PEMS were further developed as in-use testing was incorporated into the regulatory process for heavy-duty vehicles/engines to ensure emissions are controlled over the full range of speed and load combinations commonly experienced in use. The specifications for PEMS that could be utilized for in-use regulatory measurements were specified under 40 CFR 1065. A Measurement Allowance program was conducted around the time that in-use testing requirements were being put in place to evaluate the allowance that was needed to account for the differences in the accuracy between PEMS and laboratory-based testing. PEMS technology has continued to advance as PEMS become more widely used for in-use testing and for regulatory compliance in Europe, including the real driving emissions (RDE) requirements.

In additional to in-use testing with PEMS, several portable laboratories have been developed over the years that can be pulled by a heavy-duty truck while making measurements of the emissions. These trailers provided the ability of making laboratory quality measurements under in-use conditions. The U.S. EPA developed the first generation of laboratory trailers for heavy-duty trucks for in-use (Brown et al., 2000, 2002, Harris et al., 1995), although this trailer was not equipped with a full constant volume sampler (CVS) dilution tunnel capable of mimicking laboratory measurements. WVU utilized a portable laboratory that has been used in conjunction with a portable chassis dynamometer for heavy-duty vehicles. This system has been, and continues to be used, to characterize emissions of trucks, buses, refuse haulers, and other heavy-duty throughout the country over a range of different conditions. UCR researchers developed a Mobile Emissions Laboratory (MEL) that was the first full CVS laboratory trailer that could be utilized for on-road measurements (Cocker et al., 2004a, 2004b). In addition to making in-use measurements from a variety of heavy-duty trucks on road, the UCR MEL was also used in a series of studies to evaluate the Measurement Allowance needed for in-use testing with PEMS and to validate the accuracies of PEMS over the road (Durbin et al., 2007, Johnson et al., 2008, 2009, 2010, Khan et al., 2012). More recently, WVU has developed a similar trailer that is being used for on-road measurements of heavy-duty trucks.

In additional to 40 CFR 1065 compliant PEMS and mobile trailers, a full range of other methods are being developed to better characterize in-use emissions of heavy-duty trucks. These include a full range of smaller PEMS that are not designed for 40 CFR 1065 compliant regulatory measurements, but rather are primarily used for emissions inventory development or to provide a lower cost option for collecting in-use emissions from a larger fleet of vehicles. The use of remote sensing for heavy-duty vehicles has also been growing, with new technology developments still being made in this area. These technologies are discussed in greater detail below.

The remainder of this section focuses on the two main methodologies used for in-used compliance testing in the U.S. (i.e., the NTE procedure) and in Europe (i.e., the Moving Average Window [MAW] Method). Additional information about the application of PEMS and mobile trailers for in-use measurements of emissions from heavy-duty vehicles is provided in section 2.2.

2.1.3.1 Not-to-Exceed Test Procedures

The not-to-exceed (NTE) testing requirements were first introduced as part of the 1998 Consent Decrees with heavy-duty engine manufacturers. NTE testing involves testing that is done over the road with a PEMS utilized for the measurement of emissions. The applicable data for the NTE evaluation is then characterized by operation that is conducted in the *NTE control area*, which is specified by specific limits in terms of power, torque, speed, and other parameters, as discussed below. A valid NTE event is considered to be a period of time where the engine meets the NTE control area and other conditions for a period of at least 30 seconds. One of the limitations of the NTE test is the criteria for a continuous 30 seconds of operation, which can easily be invalidated if the driver briefly takes his foot off the pedal.

The NTE approach establishes a control area (the "NTE zone") which represents engine speeds and loads expected to be encountered in normal vehicle operation and use by diesel heavy-duty engines. It consists of the engine speed and load points shown in Figure 2-14:

1. All engine speeds 15% above the European Stationary Cycle speeds: $n_{lo} + 0.15 \times (n_{hi} - n_{lo})$

   where:
   n_{hi} - the highest engine speed on the power curve where 70% of the maximum engine power is still achievable,

   n_{lo} - the lowest engine speed on the power curve where 50% of the maximum engine power is still achievable.
2. All engine load points greater than or equal to 30% or more of the maximum torque value produced by the engine.
3. All operating speed and load points with brake specific fuel consumption (BSFC) values within 5% of the minimum BSFC value of the engine. The manufacturer may petition to exclude any of these speed and load points where the engine is not expected to operate in normal vehicle operation. Engines equipped with drivelines with multi-speed manual transmissions or automatic transmissions with a finite number of gears are not subject to this requirement.
4. All speed and load points where the power produced by the engine is less than 30% of the maximum power produced by the engine are excluded.

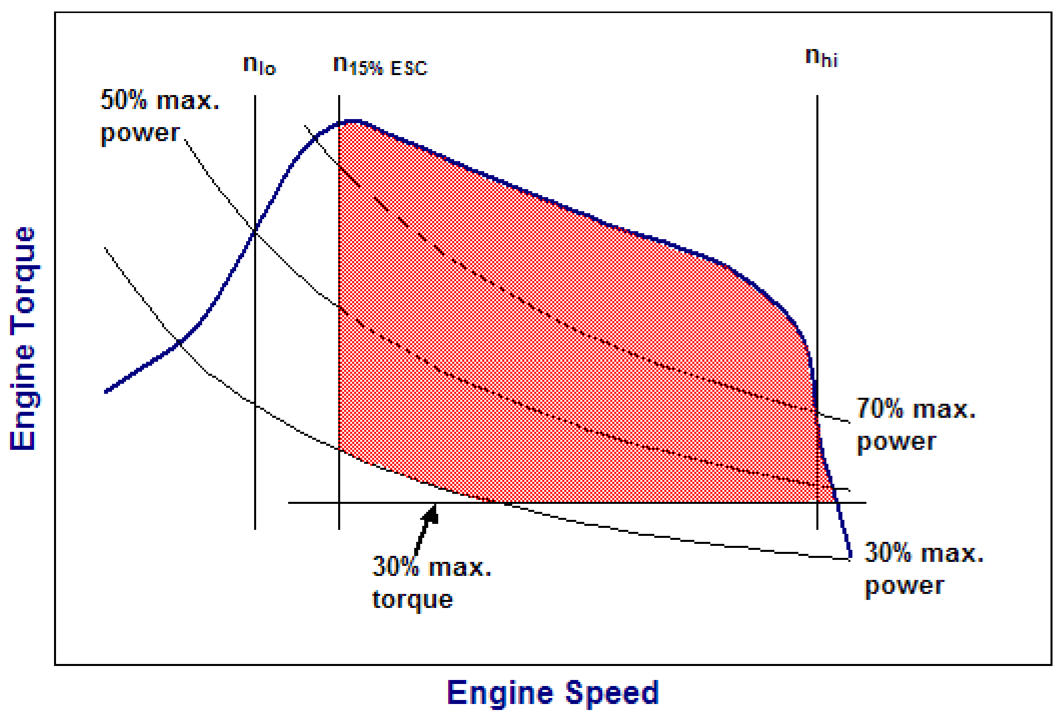


Figure 2-14. Basic NTE Zone

5. Vehicle altitude must be less than or equal to 5,500 feet (1,700 m).

6. Ambient temperature ≤ 100°F (38°C) at sea level to 86°F at 5,500 ft (1,700 m).

7. Engine operation outside of any manufacturer petitioned exclusion zone.

8. Engine operation outside of any NTE region where < of in-use time is spent.

9. Exhaust gas recirculation (EGR) equipped engines, the intake manifold temperature must be ≥ 86-100°F.

10. EGR-equipped engines, the engine coolant temperature must be ≥ 125-140°F.

11. Engine after treatment systems' temperature must be ≥ 250°C.

For Consent Decree engines meeting 2004 EPA standards and subject to NTE requirements, a *PM carve out* zone was defined at high speed and low load. PM emissions in this zone did not need to meet NTE requirements (Figure 2-15).

For 2007 and later model year engines, the PM carve out zone was eliminated. Instead, a manufacturer can petition the EPA to:

- have those speed and load points excluded from the NTE zone where the engine is not capable of operating and
- limit the amount of NTE testing in a single region of speed and load points if these operating conditions account for less than 5% of all in-use operation. This region should be generally elliptical or rectangular in shape and share some portion of its boundary with the outside limits of the NTE zone. Testing would not constitute more than 5% of the time-weighted operation in this region.

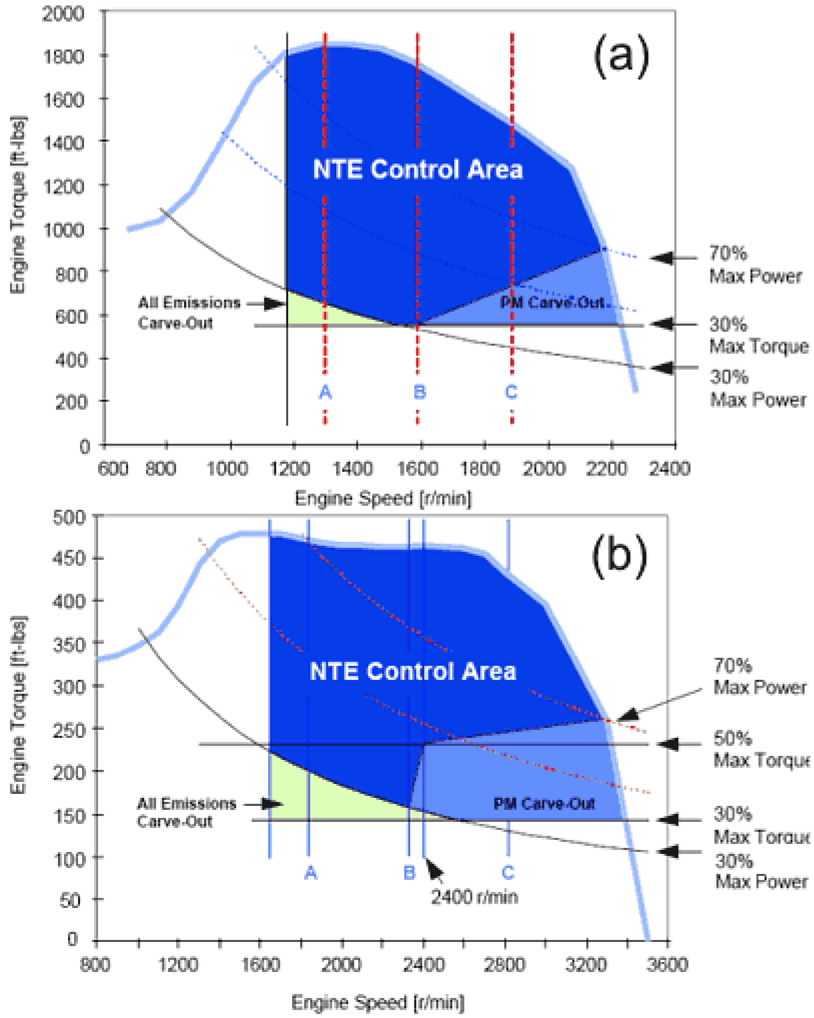


Figure 2-15. NTE Control Area for US 2004 Engines: (a) for C less than 2400 rpm; (b) for C greater than 2400 rpm (see ESC cycle for definition of speed A, B, and C)

For 2010 and newer trucks, the passing criteria for the NTE test is that at least 90% of time-weighted NTE pass events should be below a threshold value. This value is 0.45 g/bhp-hr for NOx and 0.03 g/bhp-hr for PM.

2.1.3.2 Work Based Window Approach

The current PEMS test procedure is described in Annex II of the implementing Regulation (EC) 582/2011 to the Euro VI Regulation (EC) No 595/2009. Annex II sets out requirements for checking and demonstrating the in-service conformity (ISC) of engines and vehicles. In particular it sets the procedures of ISC, the engine or vehicle selection procedure, and the PEMS test specific conditions, such as: vehicle payload, ambient conditions, engine coolant temperature, and the specifications for the lubricating oil, fuel and reagent. It also prescribes the trip and operational requirements, as well as the availability and conformity of the ECU data stream information which is required for ISC testing.

The emission evaluation is performed in accordance to the Moving Averaging Window (MAW) principle based on the reference CO_2 mass or the reference work. The mass emissions are calculated for sub-sets of the complete data set, the length of these sub-sets being determined so as to match the engine CO_2 mass or work measured over the reference laboratory transient cycle (WHTC). The passing criteria for the MAW test is that at least 90% of valid windows should have emissions below 1.5 times the applicable standard.

Moving Averaging Window (MAW) method

The averaging window method is a moving averaging process, based on a reference quantity obtained from the engine characteristics and its performance on the type approval transient cycle. The reference quantity sets the characteristics of the averaging process (i.e., the duration of the windows). Using the MAW method, the emissions are integrated over windows whose common characteristic is the reference engine work or CO_2 mass emissions. The reference quantity is easy to calculate or (better) to measure during the certification process:

- In the case of work: from the basic engine characteristics (Maximum power), the duration and the average power of the reference transient certification cycle;
- In the case of the CO_2 mass: from the engine CO_2 emissions on its certification cycle.

Using the engine work or CO_2 mass over a fixed cycle as reference quantity is an essential feature of the method, leading to the same level of averaging and range of results for various engines. Time based averaging (i.e., windows of constant duration) could lead to varying levels of averaging for two different engines. For valid windows, average power is required to be at least 10% of max engine power, and at least 50% of the windows should be valid for a given test run to be considered valid.

The first window (i.e., averaged value) is obtained between the first data point and the data point for which the reference quantity (1 x CO_2 or work achieved at the WHTC) is reached. The calculation is then moving, with a time increment equal to the data sampling frequency (at least 1Hz for the gaseous emissions).

The following sections are not considered for the calculation of the reference quantity and the emissions of the averaging window due to invalidated data originated from:

- The periodic verification of the instruments and/or after the zero drift verifications;
- The data outside the applicable conditions (e.g. altitude or cold engine).

For the sake of completeness, in the following section the details of the calculation methods are provided.

Work based method

The duration ($t_{2,i} - t_{1,i}$) of the ith averaging window is determined by:

$$W(t_{2,i}) - W(t_{1,i}) \geq W_{ref}$$

Where:

- $W(_{j,i})$ is the engine work measured between the start and time $t_{j,i}$, kWh;
- W_{ref} is the engine work for the WHTC, kWh.

$t_{2,i}$ shall be selected such as:

$$W(t_{2,i} - \Delta t) - W(t_{1,i}) < W_{ref} \le W(t_{2,i}) - W(t_{1,i})$$

Where Δt is the data sampling period, equal to 1 second or less.

The mass emissions (g/window) shall be determined using the emissions calculation formula for raw exhaust gas, as described in the European Directives 2005/55/EC- 2005/78/EC in Annex III, Appendix 2, Section 5.

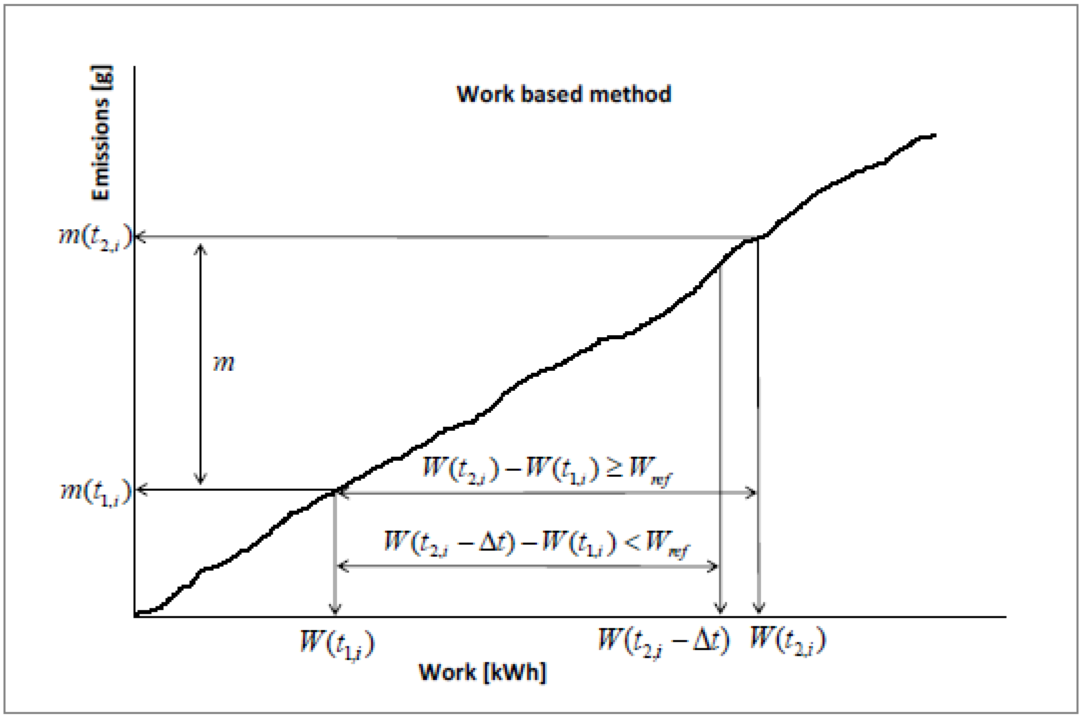


Figure 2-16. MAW worked based method

The specific emissions *e*gas (g/kWh) are calculated for each window and each pollutant in the following way:

$$e_{gas} = \frac{m}{W_{ref}}$$

Where:
m is the mass emission of the component, g/window
*W*ref is the engine work for the WHTC, kWh

Calculation of the conformity factors (CF) is as follows:

$$CF = \frac{e}{L}$$

Where:
e is the brake-specific emission of the component, g/kWh
L is the applicable limit, g/kWh

In Regulation 2016/1718 only the windows whose average power exceeds the power threshold of 10% of the maximum engine power are considered valid.

CO_2 mass based method

The duration ($t_{2,i} – t_{1,i}$) of the ith averaging window is determined by:

$$m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i}) \geq m_{CO2,ref}$$

Where:
$MCO_2(t_{j,i})$ is the CO_2 mass measured between the test start and time $t_{j,i}$, in g;
MCO_{2ref} is the CO_2 mass determined for the WHTC, in g;

$t_{2,i}$ shall be selected such as:

$$m_{CO2}(t_{2,i} - \Delta t) - m_{CO2}(t_{1,i}) < m_{CO2,ref} \leq m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i})$$

Where Δt is the data sampling period, equal to 1 second or less.
In each window, the CO_2 mass is calculated integrating the instantaneous emissions.

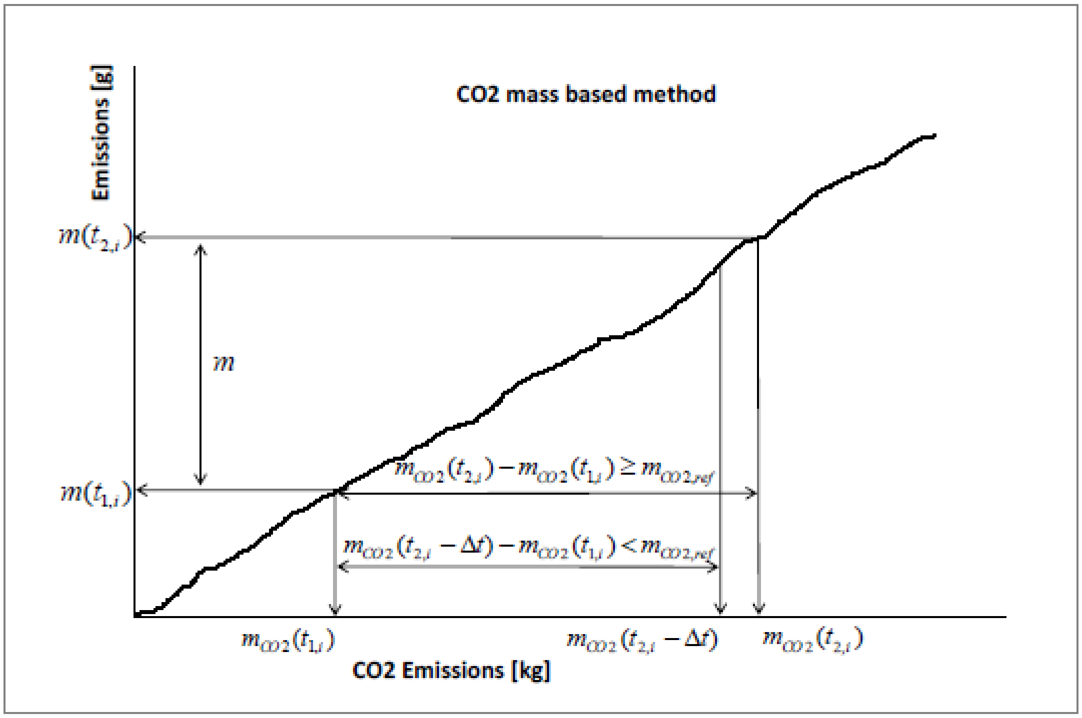


Figure 2-17. MAW CO_2 based method

The conformity factors (CF) are calculated for each individual window and each individual pollutant in the following way:

CO_2 mass based method:

$$CF = \frac{CF_I}{CF_C}$$

With $CF_I = \frac{m}{m_{CO_2,ref}}$ (in service ratio) and $CF_C = \frac{m_L}{m_{CO_2,ref}}$ (certification ratio)

Where:
m is the mass emission of the component, g/window
MCO_{2ref} is the engine CO_2 mass measured on the NRTC or calculated from:

$$m_{CO_2,ref} = 3{,}172 \cdot BSFC \cdot W_{ref}$$

m_L is the mass emission of the component corresponding to the applicable limit on the WHTC, expressed in grams.

The valid windows are the windows whose duration does not exceed the threshold duration calculated from:

$$D_{\max} = 3600 \cdot \frac{W_{ref}}{0.2 \cdot P_{\max}}$$

Where:
D_{max} is the maximum allowed window duration, s
P_{max} is the maximum engine power, kW

2.2 Review of Previous and On-going Studies

This section discusses some of the more recent studies that have evaluated emissions from 2010 and newer engines/vehicles using chassis dynamometer or in-use test methods.

2.2.1 Chassis Dynamometer Studies

2.2.1.1 CE-CERT EMA Study

The goal of this work was to obtain data on class 8 trucks with the newest emission control strategies over in-use cycles on a heavy-duty chassis dynamometer. A particular emphasis was on gathering data that can be used to improve estimates of zero mile emission rates (ZMRs) for 2010 and later model year heavy-duty engines/trucks. This information could be used to augment data being used in the development of emissions inventory models used in different levels of the regulatory process, and in particular CARB's EMFAC2013 model. Five vehicles were tested in this study. The vehicles were all heavy-duty class 8 trucks with the latest generation of emissions control technology, including a DPF and a SCR system for NO_x emissions. The vehicles tested ranged in model year from 2012 to 2015, with 4 of the 5 engines being 2014 or newer. The vehicle matrix included 2

Cummins engines and one engine each from Detroit Diesel Corporation (DDC), Volvo, and Navistar. The engines/vehicles were certified to a 0.2 g/bhr-hp or lower NOx certification limit, with the exception of one engine that was certified to a 0.35 g/bhr-hp NOx standard. Each vehicle was tested on UCR's heavy-duty chassis dynamometer over the four phases of the HHDDT schedule developed by CARB (i.e., idle, creep, transient, and cruise), the HHDDT short or (HHDDT-S) cycle, which is a high speed cruise schedule, and the UDDS, a cycle considered to be the chassis dynamometer equivalent of the engine dynamometer transient test. Three of the 5 test vehicles were also tested at CARB's heavy-duty chassis dynamometer testing facility in Los Angeles.

2.2.1.2 South Coast Air Quality Management District In-Use Chassis Dynamometer Study

This study, funded by the SCAQMD, involved coordinated testing by UCR and WVU to conduct chassis dynamometer testing of twenty-four model year (MY) 2007-2012 heavy-duty vehicles from different vocations and fueling technologies. The test vehicle vocations included goods movement, refuse, transit and school bus applications, and the test cycles used for the specific vocations were port drayage truck cycles for goods movement, SCAQMD refuse truck cycles for the refuse applications, and Orange County Transportation Authority (OCTA) and CBD cycles for transit applications. The Heavy Duty-UDDS was a common cycle for all vocations. The test matrix involved eight diesel and two propane vehicles tested by UCR, five natural gas and four dual-fuel vehicles to be tested on a chassis dynamometer by WVU, and five diesel vehicles tested by both WVU and UCR for an inter-laboratory comparison. Diesel engines tested were either U.S. EPA 2007 emissions compliant or U.S. EPA 2010 emissions compliant. The U.S. EPA 2007 emissions compliant engines were equipped with exhaust gas recirculation (EGR) technology and DPFs, while the U.S. EPA 2010 emissions compliant engines were of two types: a) with EGR and DPF only b) with DPF and SCR.

For the UCR portion of the study, NO_x results covered a wide range of emission factors, where the emissions depended on the certification standard, vehicle application, driving cycle, and manufacturer (Miller et al., 2013). Emissions for the Hot and Cold Start UDDS Cycles for the Goods Movement and Refuse Hauler Vehicles are shown in Figure 2-18 and Figure 2-19, on a g/bhp-hr and g/mi basis. On a g/bhp-hr basis, the results were below the certification standard for the hot start UDDS cycles, ranging from 0.06 to 0.27 g/bhp-hr. Emissions were slightly higher for the cold start UDDS cycle, ranging from 0.23 to 0.46 g/bhp-hr. Hot start UDDS emissions for the Goods Movement and Refuse Truck Vehicles ranged from 0.25 to 1.27 g/mi, while cold start UDDS emissions ranged from 1.04 to 2.16. Larger variations in emissions were seem over a wider range of test cycles, as shown in Figure 2-20. For the goods movement vehicles, emissions were highest for the near dock port cycle (ranging from 0.87 to 8.29 g/mi), followed by the local port cycle (ranging from 0.63 to 4.91 g/mi), and the regional port cycle (ranging from 0.41 to 1.35 g/mi). For the refuse trucks over the refuse truck cycle emissions ranged from 0.51 to 1.22 g/mi.

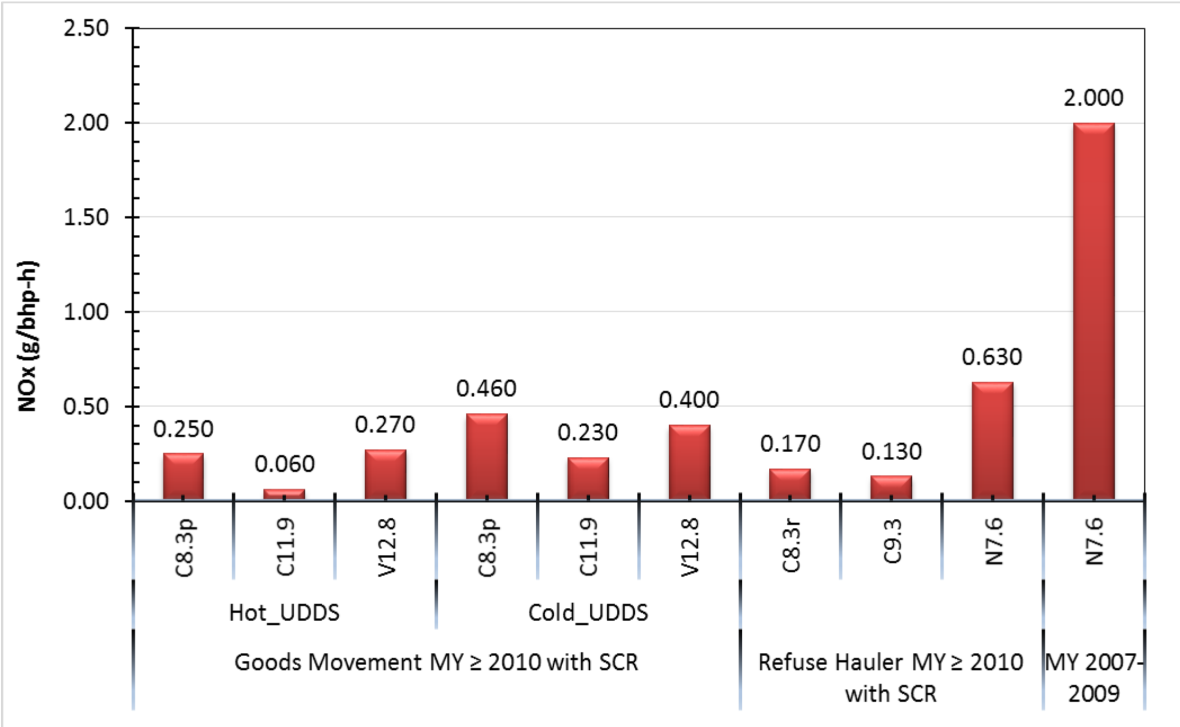


Figure 2-18. Brake Specific NOx Emissions for the Goods Movement and Refuse Hauler Vehicles for the Hot and Cold Start UDDS Cycle

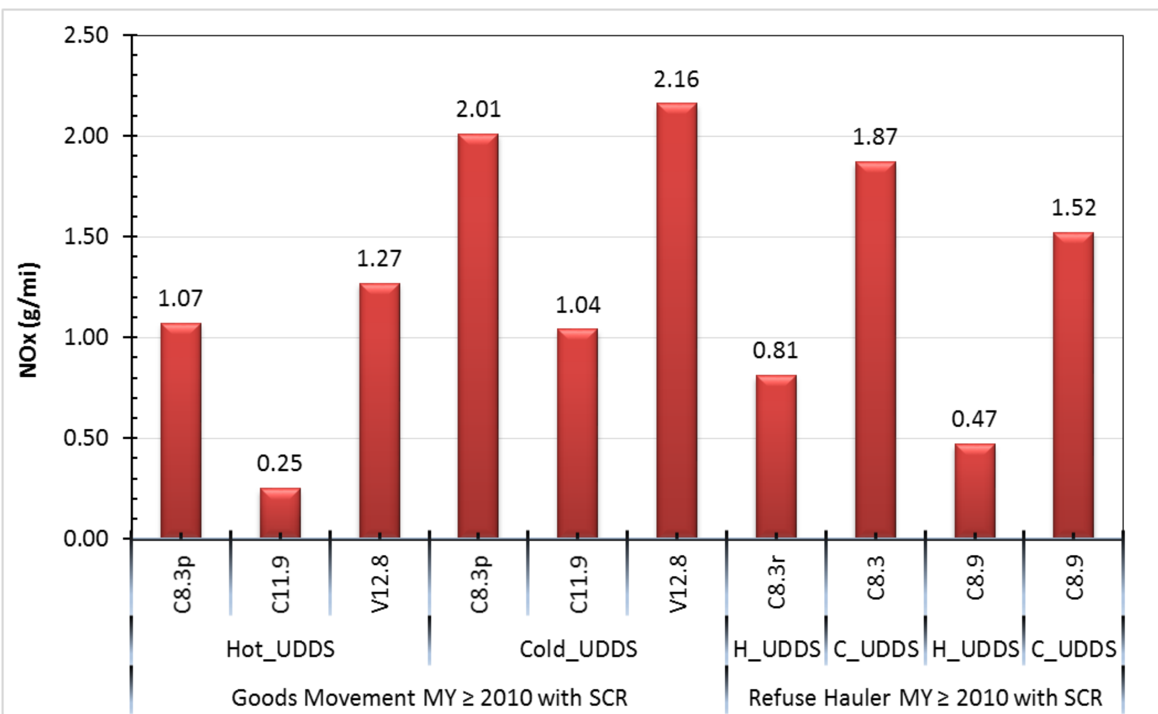


Figure 2-19. NOx Emissions (g/mi) for the Goods Movement and Refuse Truck Vehicles for the Hot Start and Cold Start UDDS Cycle.

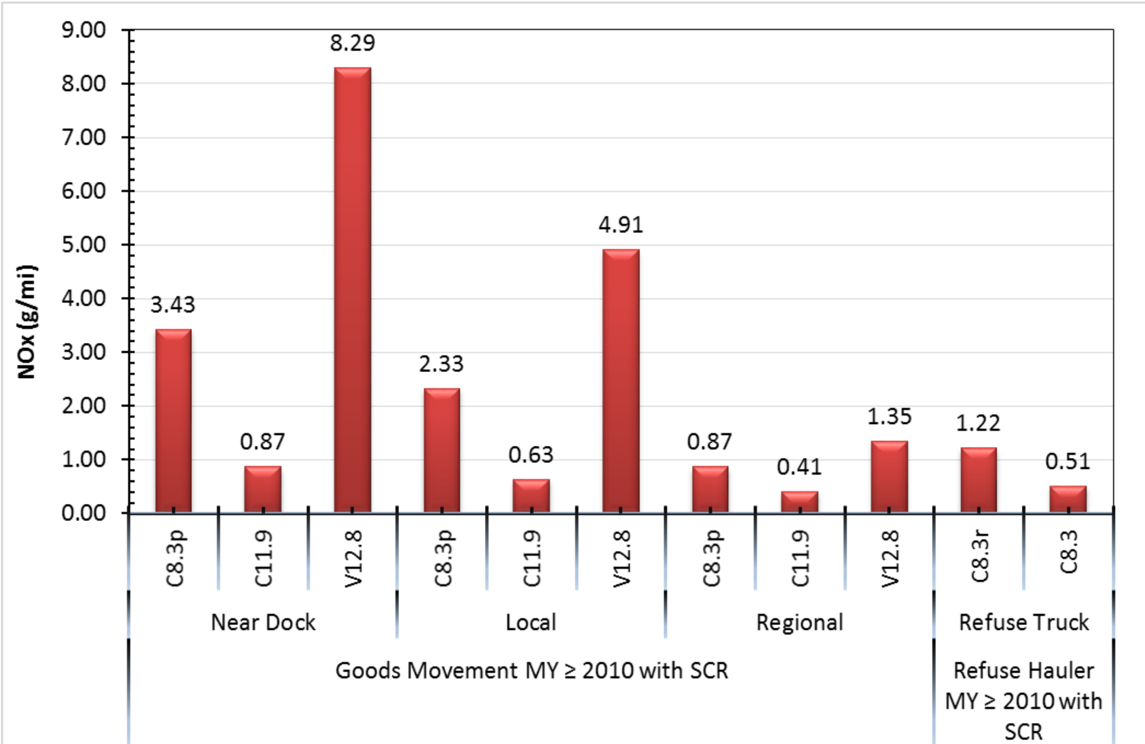


Figure 2-20. NOx Emissions (g/mi) for the Goods Movement Vehicles for the the Near Dock Port Cycle, the Local Port Cycle, and the Regional Port Cycle and for the Refuse Hauler Trucks for the Refuse Truck Cycle.

The NO_x impact of SCR equipped diesel engines depends on the vehicles' duty cycles and manufacturers' implementation for low temperature SCR performance. The SCR temperature was below 250°C approximately 80% of the time for the near dock port cycle, 65% of the time for the local port cycle, and approximately 45% of the time for the regional port cycle. The percentage of time below 250°C varied significantly between manufacturers, from 8% to 30% for the near dock cycle, and from 41% to 64% for the regional cycle. A comparison of the NOx emissions and percentage of time below 250°C for three goods movement vehicles is provided in Figure 2-21. This included trucks with a 2010 Cummins ISC-300 (vehicle 6), a 2011 Cummins ISX-11.9 (vehicle 7), and a 2011 Volvo MPB 445c engine (vehicle 8). The difference in time below 250°C suggests some manufacturers have better strategies for maintaining high exhaust temperatures than others. Most NO_x emissions from SCR-equipped diesel refuse vehicles were produced during the compaction portion of the in-use test cycle. The high NO_x emissions corresponded with a low SCR exhaust temperature, where the emissions increased from 0.27 g/bhp-hr NO_x for the transient and curbside cycles to 3.8 g/bhp-hr NO_x for the compaction cycle.

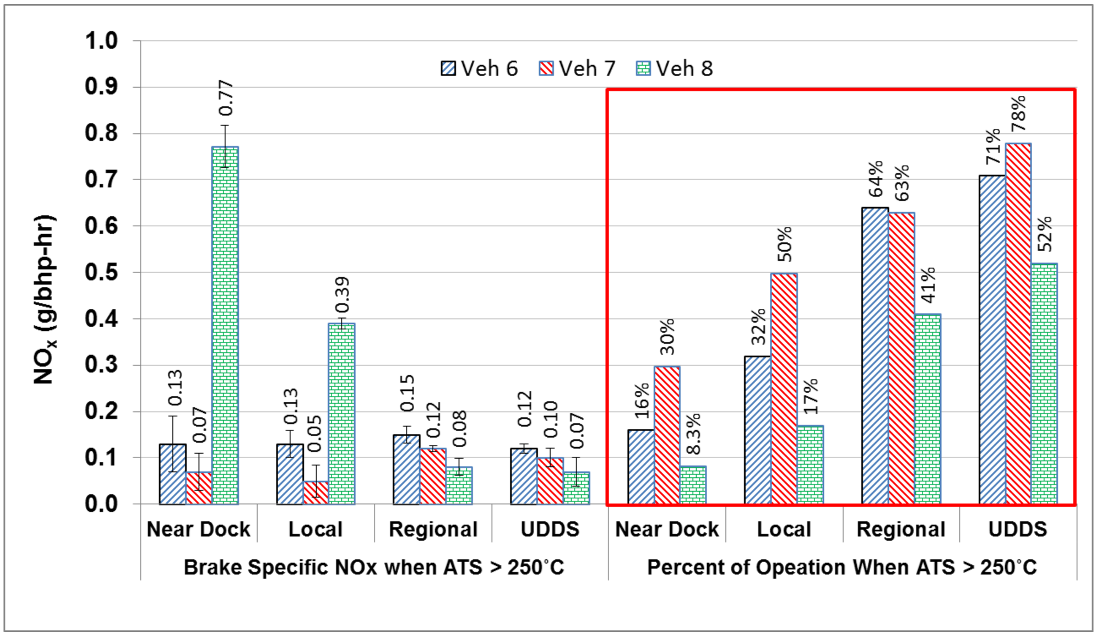


Figure 2-21. NO_x emissions for ATS >250°C (g/bhp-hr) b) percent time for ATS >250°C

The WVU testing included both diesel and natural gas engine equipped vehicles, with the diesel vehicles being in the goods movement and refuse hauler categories (Carder et al., 2014; Thiruvengadam et al., 2015). The emissions results for the diesel goods movement vehicles are shown in Figure 2-22. This includes engines certified at 1.2 g/bhp-hr NOx (MY 2007- 2009) and equipped with a DPF [category IV], engines certified at over 0.20 g/bhp-hr (MY 2011) equipped with only a DPF and no SCR [Category VII], and engines certified below 0.20 g/bhp-hr equipped with both DPF and SCR [Category VIII]. The category VIII vehicle was powered by Mack MP-7 engine equipped with a DPF and SCR. Over the UDDS cycle the category IV, VII and VIII vehicles emitted 8.77 g/mi, 5.51 g/mi and 1.98 g/mi of NOx emissions, respectively. While comparing the two US-EPA 2010 emissions compliant vehicle it can be observed that the NOx emissions from the SCR equipped diesel was 64% lower than that of a high EGR non-SCR diesel engine over the UDDS cycle. The near-dock cycle resulted in 0% SCR activity and as a result the average distance-specific emission of NOx was measured to be 9.04 g/mi from the SCR equipped diesel vehicle, similar to the 9.50 g/mi average distance-specific NOx emissions from the MY 2009 vehicle. The results show that during periods where the SCR system is not operating the distance specific NOx emissions from 2010 0.2 g NOx engines are similar to those from diesel engine's certified to the 1.2 g/bhp-hr standard. The local drayage cycle resulted in partial SCR activity and hence the distance-specific NOx emission was measured to 5.89 g/mi from the category VIII goods movement vehicle. NOx emissions were also evaluated on a bhp-hr basis, and as a function of exhaust temperature for the 0.2 g NOx engine, as shown in Figure 2-23 over the UDDS and port drayage cycles. Brake-specific NOx emissions over the UDDS, regional, local and near-dock cycle were measured to be 0.41 g/bhp-hr, 0.36 g/bhp-hr, 1.26 g/bhp-hr and 1.79 g/bhp-hr respectively. The SCR activity percentages shown in the figure reveal poor SCR activity over all types of drayage operation. The near-dock drayage operation resulted in exhaust temperatures that were not conducive for SCR activity. Similarly, exhaust temperatures over the local and regional cycles were more than 60% of the time below the threshold limit of 250°C.

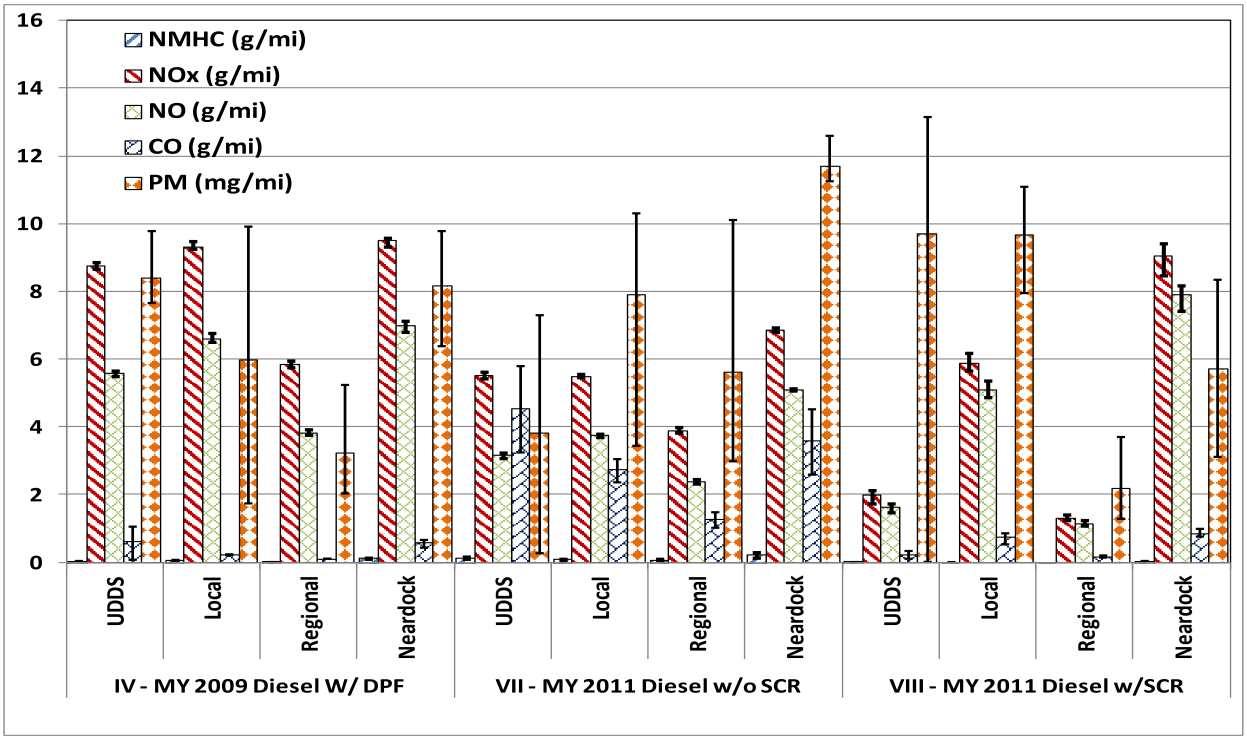


Figure 2-22. WVU Results for Diesel Goods Movement Vehicles

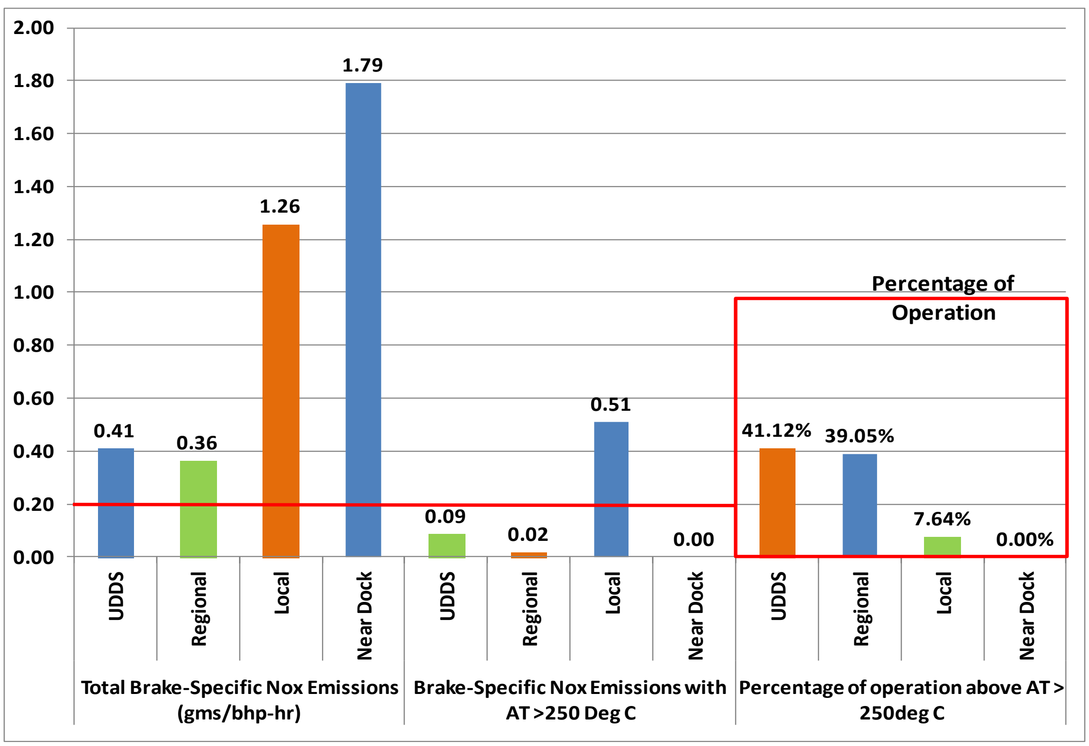
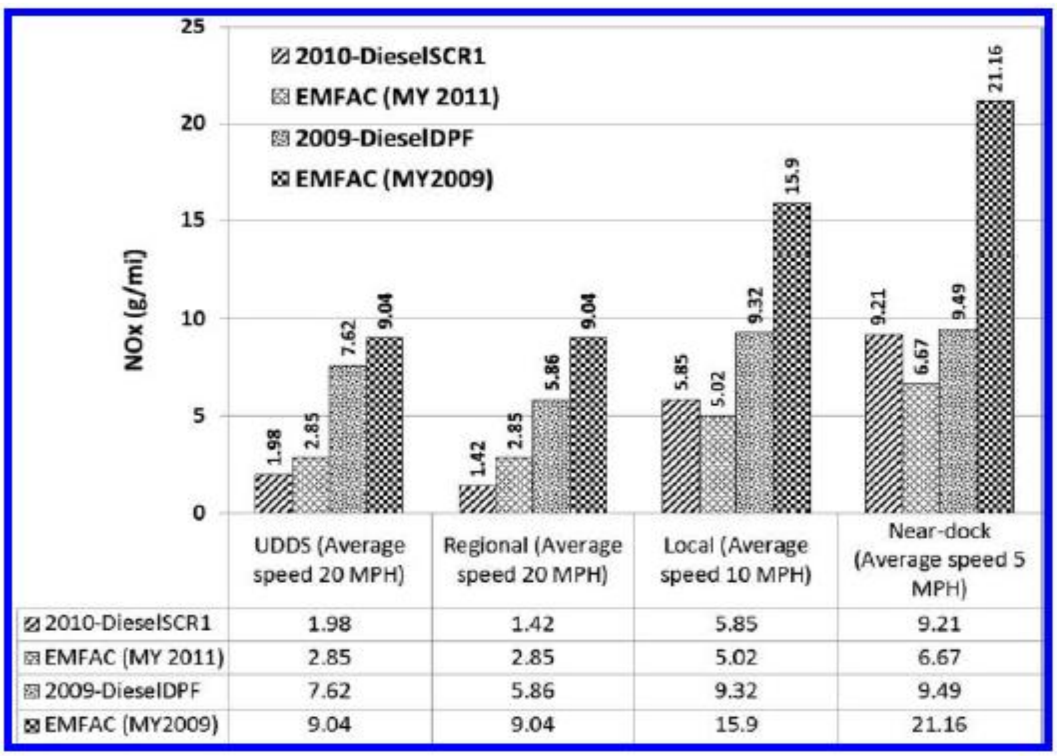


Figure 2-23. Brake-specific NOx emissions and percentage SCR activity of the WVU SCR equipped diesel goods movement vehicle.

WVU also did some preliminary comparisons of their results with EMFAC model estimates (Thiruvengadam et al., 2015). Figure 2-24 shows the comparison of NOx emissions rate projected by EMFAC averaged for the state of California for MY 2009 and 2011 HD tractor with results for 2010-DieselSCR1 and 2009-DieselDPF. The EMFAC database was queried for annual average statewide emissions rate for the calendar year 2014 for the MY 2009 and 2011 T7 truck category (i.e., heavy heavy-duty tractors). The speed bins were chosen to match the average speeds of the cycles tested during this study. Figure 2-24 shows the respective average speeds of the different cycles for which the EMFAC database was queried. NOx emissions rate from EMFAC for the MY 2011 vehicle were 30% higher compared to the HD-UDDS emissions rate and 50% higher compared to the regional drayage cycle with a similar average speed. For the local and near-dock driving cycles with average speeds of 10 and 5 mph, respectively, EMFAC predictions are 10% and 27% lower, respectively. This can be linked to the inability of the model to predict activity of the aftertreatment system and hence under predict emissions during periods of nonoperation of SCR. EMFAC also showed higher emission for the 20 mph speed bin with two different SCR activity profiles resulting from HD-UUDS cycle (41% SCR activity) and regional drayage cycle (58% SCR activity). The predictions of EMFAC were closest with HD-UDDS. Since, the parent data for the EMFAC is based on emissions rates derived from the HD-UDDS cycle and FTP engine certification data, the extrapolation of those emissions rates to engine operation significantly different from those cycles will result in large deviations from actual NOx emissions rates. Predicting SCR activity as a function of simple vehicle speed is challenging since exhaust temperature is a function of engine load and thermal management strategy. The authors suggested that factoring in data from real-world driving cycles could lower differences between EMFAC model prediction and real-world emissions rate.



	UDDS (Average speed 20 MPH)	Regional (Average speed 20 MPH)	Local (Average speed 10 MPH)	Near-dock (Average speed 5 MPH)
2010-DieselSCR1	1.98	1.42	5.85	9.21
EMFAC (MY 2011)	2.85	2.85	5.02	6.67
2009-DieselDPF	7.62	5.86	9.32	9.49
EMFAC (MY2009)	9.04	9.04	15.9	21.16

Figure 2-24. Comparison of NOx emissions rate between chassis driving cycle and respective speed bins from output of EMFAC predictions.

Two US-EPA 2010 emissions compliant refuse trucks were tested by WVU as part of this study. Refuse truck from vehicle Category VII was certified at 0.46 g/bhp-hr and the vehicle from category VIII was certified at 0.18 g/bhp-hr over the FTP certification cycle. Note that the class VIII truck was tested at 56,000 lbs., which is higher than used for the other vehicles, while the category VII vehicle was tested at 33,000 lbs. As such, care must be taken with any emissions comparisons. Figure 2-25 shows the distance-specific emissions results from two diesel refuse trucks from category VII and category VIII. NOx emissions from the category VIII refuse truck (with SCR) were measured to be 1.25 g/mi, 0.71 g/mi and 0.50 g/mi over the UDDS, AQMD refuse truck cycle and refuse truck cycle with compaction, respectively. The NO/NOx ratio for this engine was measured to be 0.64, 0.71 and 0.53 over the UDDS, AQMD refuse truck cycle and the refuse truck cycle with compaction respectively. Figure 2-26 shows the brake-specific NOx emissions and SCR catalyst activity above 250°C for the category VIII truck. The results show that the SCR activity for this vehicle was 79%, 95.7% and 87.6% over the UDDS, refuse truck cycle and the refuse truck cycle with compaction. The brake-specific NOx emissions over the UDDS, refuse truck cycle and the refuse truck compaction cycle were 0.26 g/bhp-hr, 0.10 g/bhp-hr and 0.12 g/bhp-hr respectively. It is to be noted that the SCR refuse truck was powered by a 8.3 liter, 300HP Cummins engine. A smaller engine powering a 60,000 lbs vehicle enabled sustained operation of the engine at higher loads, and as a result higher exhaust temperatures. The engine also frequently triggered SCR thermal management to increase exhaust temperatures to SCR activity range of between 200 to 250°C. A combination of SCR thermal management strategy and downsized engine and after-treatment system contributed to a greater percent activity of the SCR and consequently lower NOx emissions.

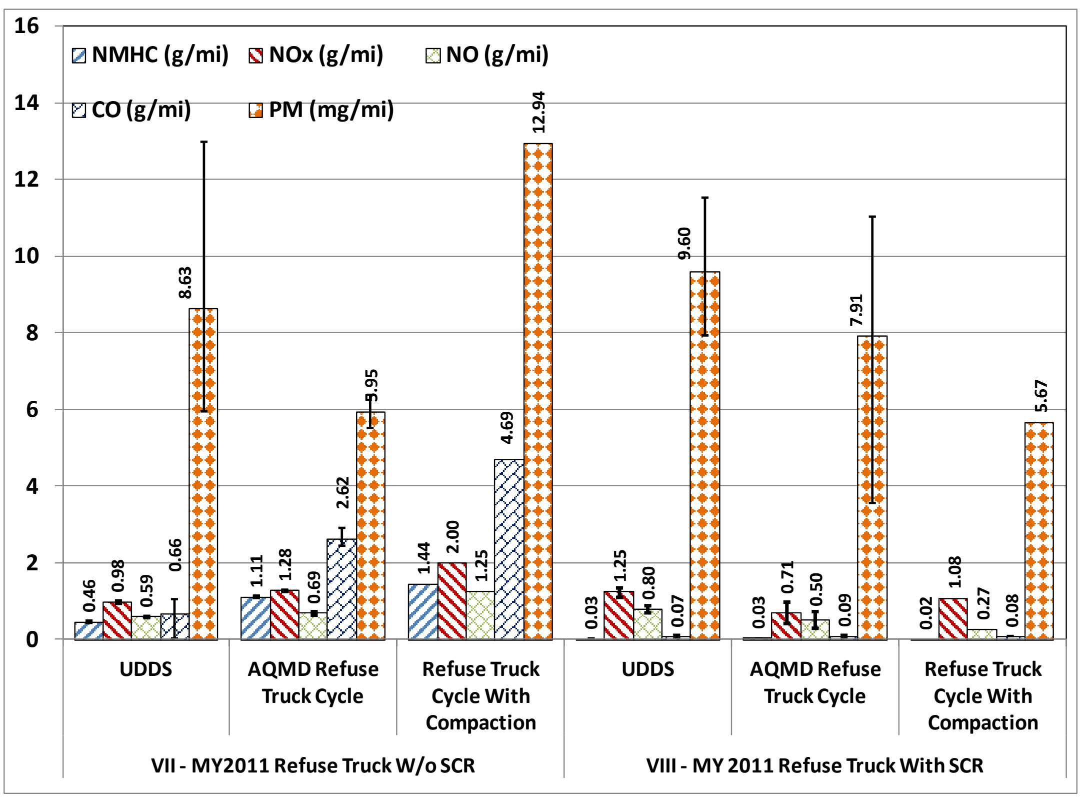


Figure 2-25. Distance-specific regulated emissions results of USEPA 2010 compliant diesel refuse trucks

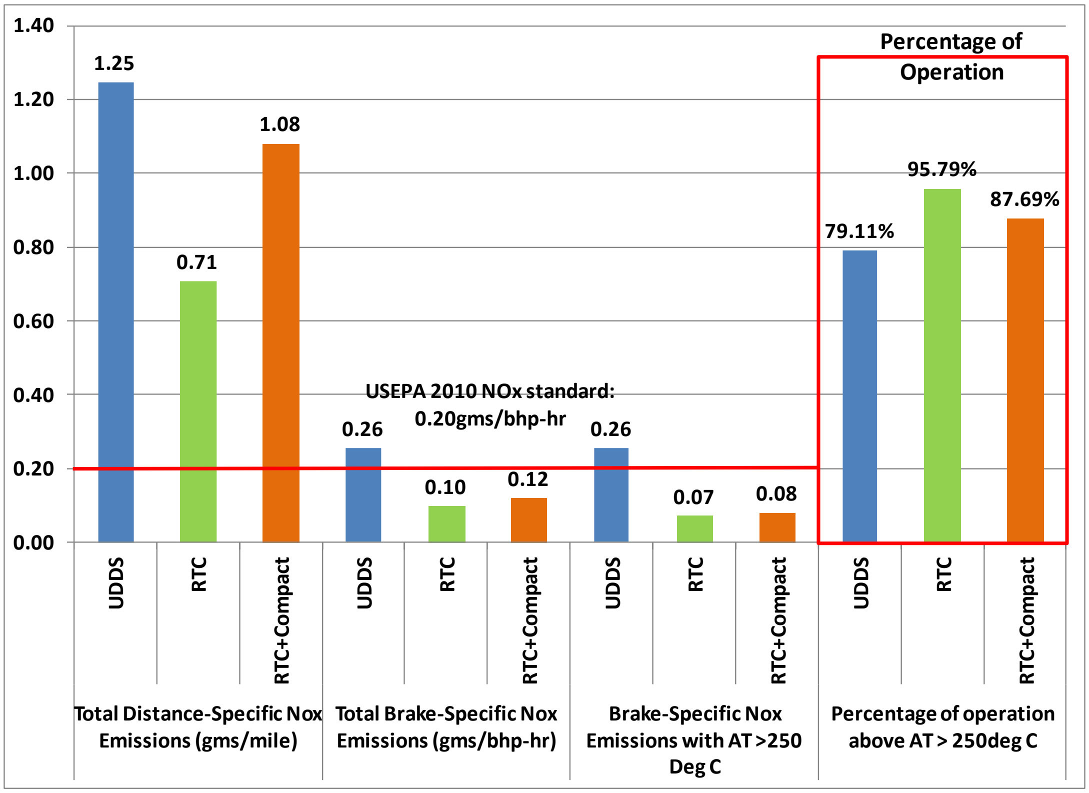


Figure 2-26. Brake-specific NOx emissions and after-treatment activity of SCR diesel refuse truck

2.2.1.3 California Air Resources Board Chassis Dynamometer Studies

CARB has been utilizing chassis dynamometer testing data to develop emissions factors for its EMFAC model for a number of years. For the EMFAC2007 model, in-use emissions data were primarily obtained from the CRC E-55/59 study (Clark et al. 2006, 2007) coupled with estimates for 2007 and newer model year vehicles. For the EMFAC2013 model, a greater emphasis was placed on developing emission factors for newer PM and NOx aftertreatment control devices, and incorporating in-use emissions data from 2007 and newer engines/vehicles. As part of its efforts to develop emission factors for 2007 and newer vehicles, CARB conducted a chassis dynamometer testing program (CARB, 2013). Of the vehicles tested, 5 vehicles were equipped with 2010 and newer heavy-duty diesel engines. The 5 engines tested were all 2010 or 2011 model years, with 2 certified to the 0.20 g/bhp-hr NOx standard, with both of these engines being from the same manufacturer. Additionally, 2 of the 5 engines were a technology that utilized only EGR for NOx control that had a very limited production run. The vehicles were testing over the UDDS, the four main phases of the HHDDT schedule (i.e., idle, creep, transient, and cruise) (Gautam, et al. 2002), and the HHDDT short or (HHDDT-S) cycle. Based on this and other data, emissions factors for EMFAC2013 were estimated to be 2.33 g/mi for 2010-2012 vehicles and 1.89 g/mi for 2013 and newer vehicles.

CARB is also conducting truck and bus surveillance program (TBSP) to develop emissions factors for its EMFAC model. So far, this program has tested a total of 20 HDDVs with 2010 and newer model years. NOx emission rates over the UDDS cycle for these vehicles are provided in Figure 2-27. Overall, the NOx emission rates of the model year 2013 and newer engines were lower, compared with those of the model year 2010 to 2012 engines for the same manufacturers, except for two 2013 Cummins engines. There are significant differences in NOx emission rates between different engine manufacturers. The NOx emission rates of Navistar (only one vehicle), Paccar and DDC engines were below 2 g/mi, except for one 2013 Paccar. The NOx emission rates of Cummins and Volvo engines ranged from 3.3 to 9.7 g/mi, except for one Cummins engine with the value lower than 1 g/mi.

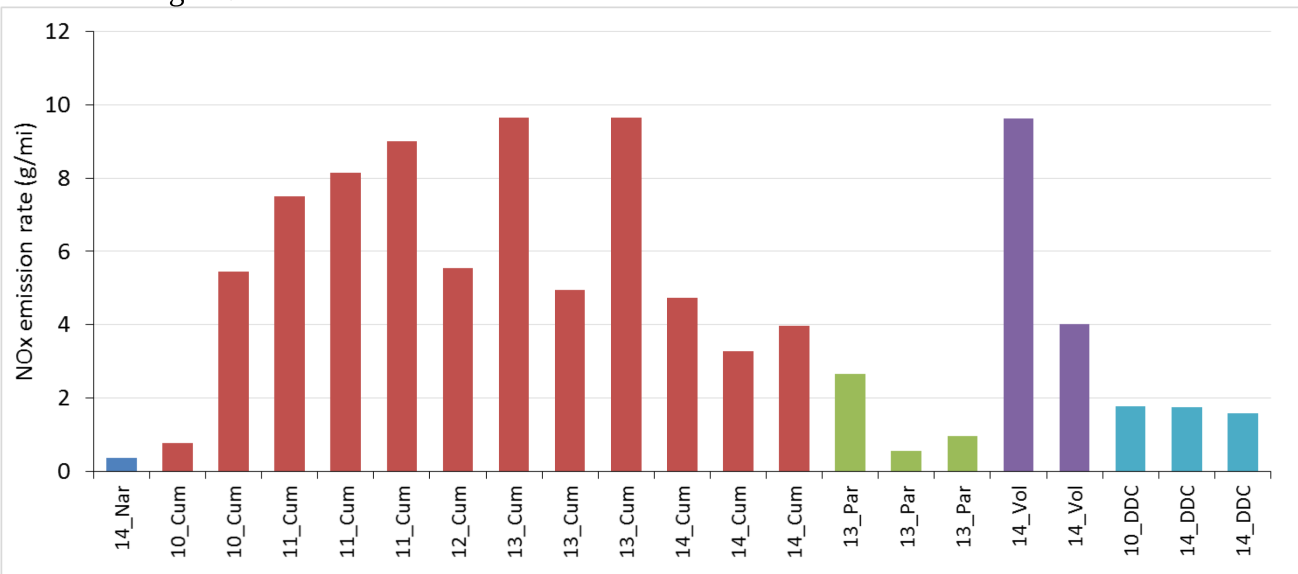


Figure 2-27 NOx emission rates from CARB truck and bus surveillance program (TBSP)

2.2.1.4 Real-Time Results for Chassis Dynamometer Emissions Studies

Additional analyses were conducted for the SCR-equipped engines to evaluate the variation in NOx emissions as a function of exhaust temperature for a number of the different studies. This section provides an analysis of real-time data from a subset of vehicles from different studies.

For the UCR-SCAQMD study, the SCR equipped engines were within their certification standards and were typically below 0.2 g/bhp-h, except for low SCR temperature operation. Figure 2-28 shows the cumulative NO_x emissions, instantaneous SCR inlet temperature and vehicle speed for a class 8 Freightliner equipped with a 2011 Cummins 11.9 liter engine. The figure is typical for SCR equipped diesel engines, where cold start UDDS NO_x emissions can be as high as 2.3 g/bhp-hr compared to an equivalent warm start UDDS test of 0.006 g/bhp-h. Although cold start emissions do not contribute significantly to the inventory, it is important to consider the extreme nature of cold start emissions if vehicles are allowed to cool frequently. The NO_x emissions accumulated in 1 mile after a cold start were equivalent to emissions accumulated during 32 miles of running hot.

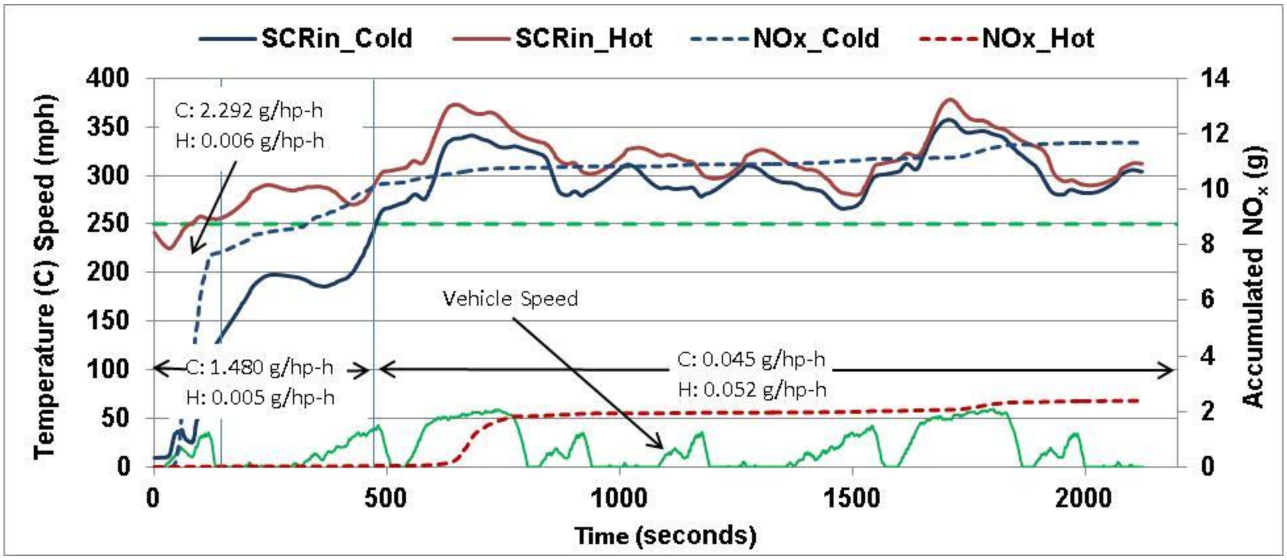


Figure 2-28. Accumulated NOx emissions during hot and cold start UDDS testing

Figure 2-29 and Figure 2-30 show the real-time SCR temperature and the NOx concentrations of the hot UDDS cycle for a 2014 Cummins and 2012 Volvo truck both from the UCR-EMA study, respectively, while Figure 2-31 shows the real-time SCR temperature and NOx concentrations for a 2011 Cummins #1 for a cold UDDS cycle from the UCR SCAQMD study. A significantly larger peak in NOx emissions was observed at the beginning of the cold start when the SCR temperature was below 150˚C than the beginning of the hot start when the SCR temperature was above 200˚C, as seen by comparing Figure 2-29 and Figure 2-31. The 2011 Cummins #1 was totally warmed up by driving for 180 secs, so the SCR temperature was above 250˚C at the beginning of the cycle and there is no significant NOx peak. The 2014 Cummins showed multiple NOx peaks up to 95 ppm when the SCR temperature was below 220˚C. SCR catalysts are expected to be operating at temperatures where the NOx conversion efficiencies are robust, leading to relatively low tailpipe out NOx emissions. Where higher SCR temperatures were seen for vehicles, lower NOx emissions were emitted. Under these conditions, even though the cold start for the 2014 Cummins showed NOx emissions, the higher SCR temperatures throughout the rest of the cycle contributed to lower integrated emissions than those of the 2014 Cummins for the hot start UDDS cycle. The average SCR temperatures for the 2012 Volvo were much lower than the average of the 2014 Cummins during the same cycle. The 2012 Volvo showed more peaks in NOx emissions, which lead to the higher integrated NOx emissions in Figure 2-37.

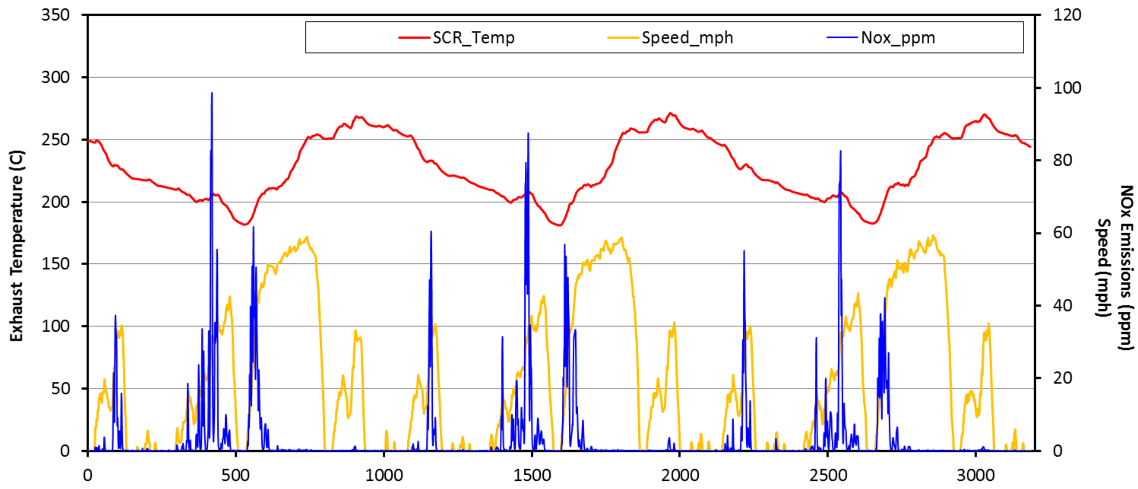


Figure 2-29 Hot-UDDS Cycle for 2014 Cummins

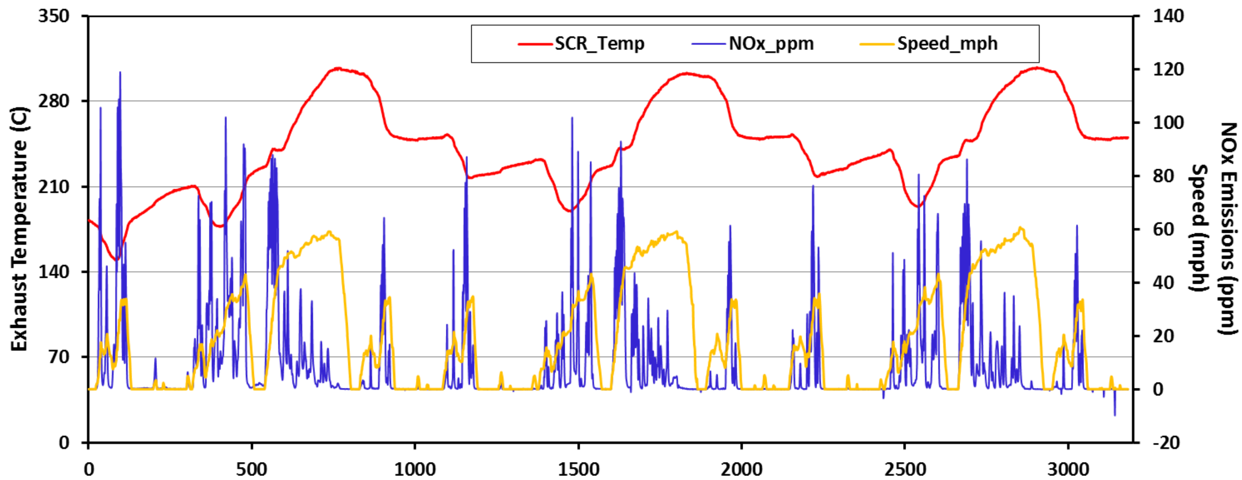


Figure 2-30 Hot-UDDS Cycle for 2012 Volvo

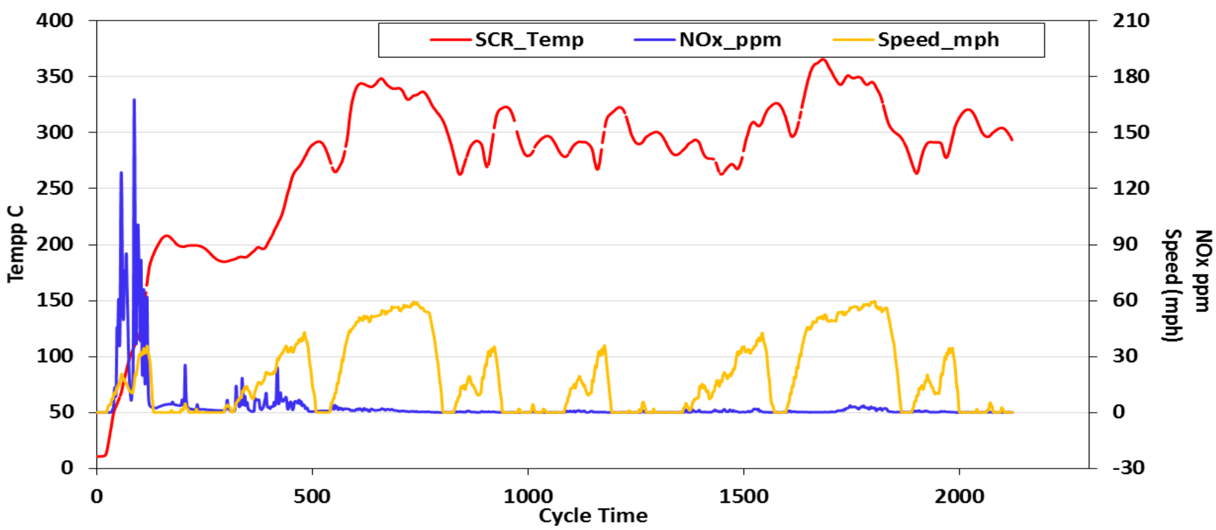


Figure 2-31 Cold-UDDS Cycle for 2011 Cummins #1

Figure 2-32 and Figure 2-33 show the real-time SCR temperature and the NOx concentrations for the Cruise 55 cycle for the 2014 Cummins and 2012 Volvo, respectively, from the UCR-EMA study. At the beginning of the cruise cycle for the 2014 Cummins, when the SCR temperature is below 240˚C, NOx emissions showed a peak of 30 ppm. When the vehicles were in the high speed driving mode portion of the cycle with the SCR temperature above 240˚C, real-time NOx emissions were found to be flat and near the zero line. For the 2012 Volvo, two huge peaks were observed at the beginning of the cruise cycle. For the rest of the cycle, when the SCR temperature was above 300˚C, a number of smaller peaks around 10 ppm were found. Comparing the vehicles over this cycle, the integrated NOx emission factor of the 2012 Volvo was eight times higher than that of the 2014 Cummins.

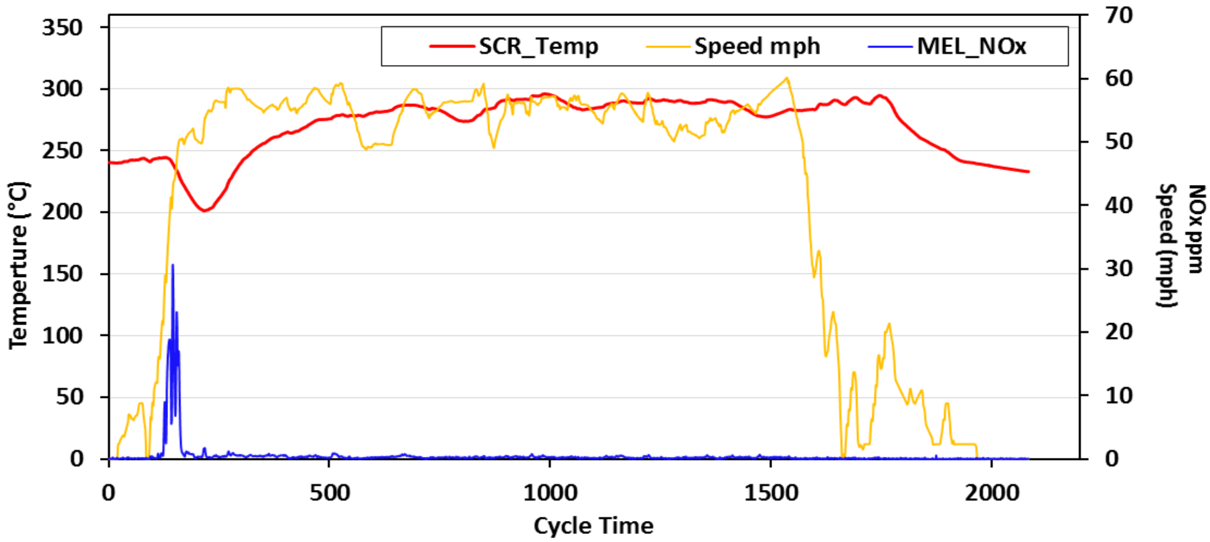


Figure 2-32 Cruise Cycle for 2014 Cummins

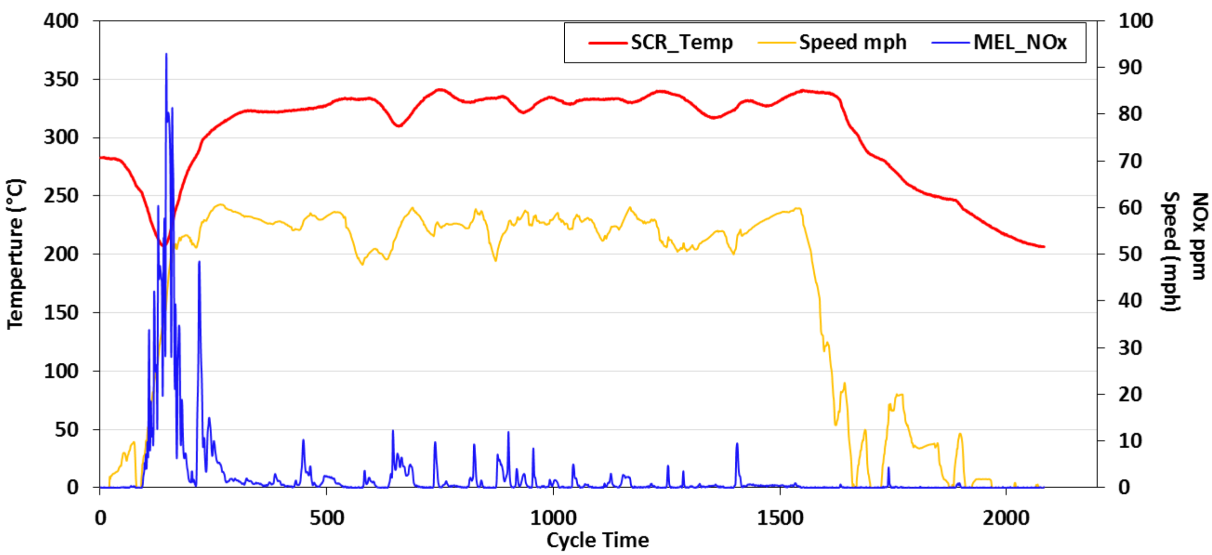


Figure 2-33 Cruise Cycle for 2012 Volvo

Figure 2-34, Figure 2-35 and Figure 2-36 show the real-time SCR temperature and the NOx concentrations for the 2011 Cum #1 from the UCR-SCAQMD study for the Near dock cycle, Local cycle and Regional cycle, respectively. For the integrated NOx emission factors, the Near Dock cycle showed the highest NOx emissions, while the Regional cycle showed the lowest NOx emissions. The driving trace for the Regional cycle was more aggressive than other two driving cycles, which lead to the higher exhaust temperatures. Figure 2-36 with the Regional cycle showed the highest SCR temperatures and the lowest NOx peaks among the three driving traces. Even though similar SCR temperatures were observed at the beginning of the Near Dock and Local cycles, the rest of the Local cycle included more transient driving to keep the SCR temperature above 250°C, leading to lower NOx emissions than the Near Dock.

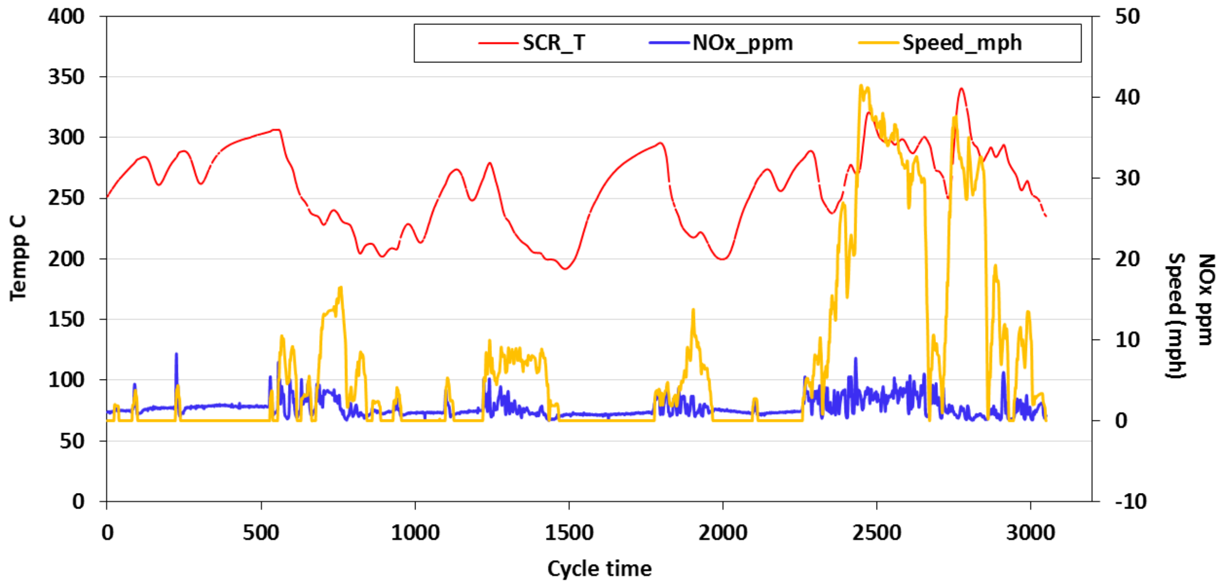


Figure 2-34 Near Dock Port Cycle for 2011 Cummins #1

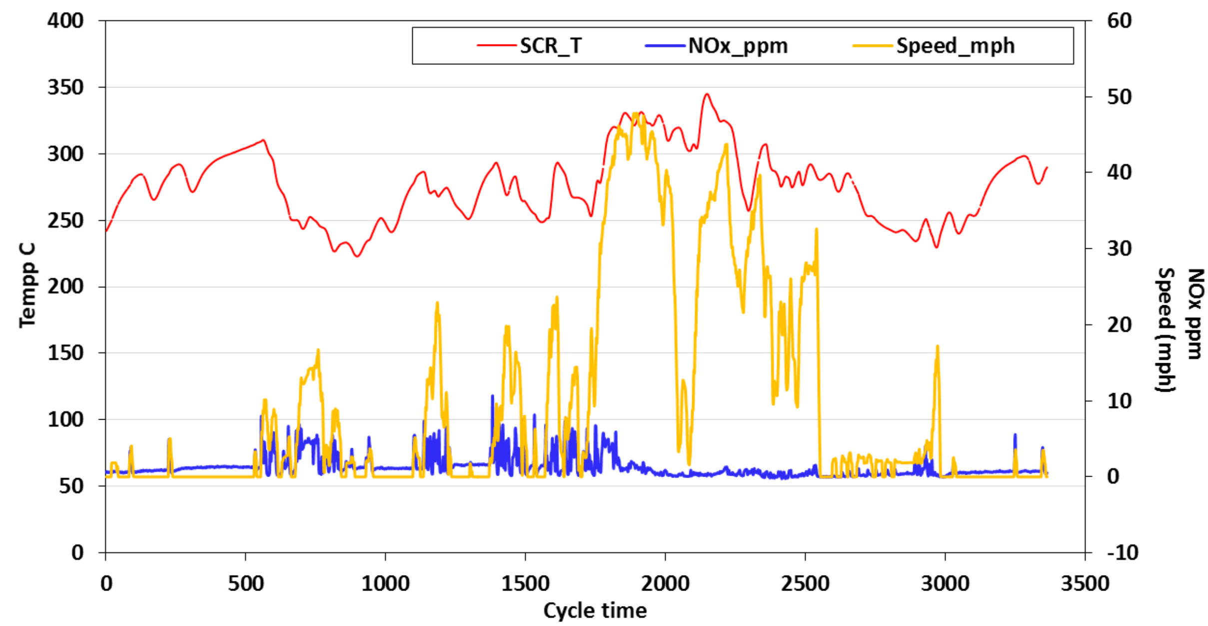


Figure 2-35 Local Port Cycle for 2011 Cummins #1

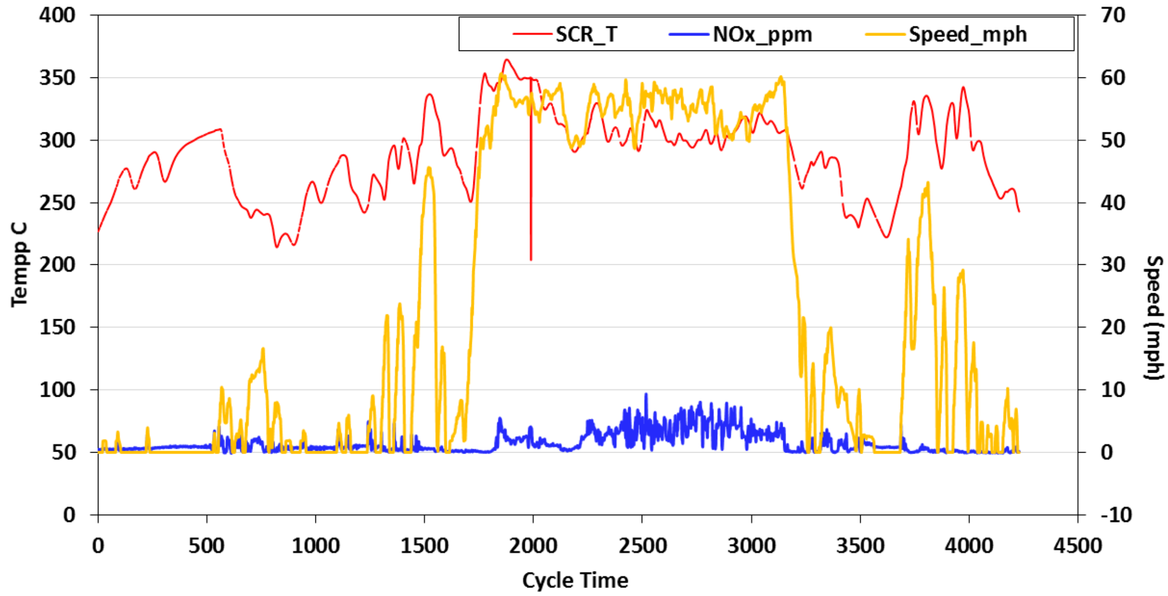


Figure 2-36 Regional Port Cycle for 2011 Cummins #1

2.2.1.5 Summary Results for Chassis Dynamometer Emissions Studies

This section summarizes the results from 2010 and new heavy-duty trucks for the CE-CERT EMA study, the SCAQMD In-Use Chassis Dynamometer study and CARB Chassis Dynamometer Studies. This includes six Cummins, one DDC, four Volvo, and six Navistar engine equipped vehicles with model years newer than 2010. A summary of the vehicle inventories for the chassis dynamometer tests is provided in Table 2-8. Note that Navistar engines initially utilized EGR to meet the 2010 NOx standard, but then subsequently switched to SCR, so the 2010 and 2011 Navistar engines are listed separately from the 2014 Navistar engine that utilized SCR in Table 2-8.

Table 2-8 Vehicle inventories for Chassis tests

Vehicle ID	Maker	Engine Model	Model Year	Horsepower	Vehicle Mileage	Standard/FEL Level	Certification Level	Studies
		SCR equipped				**g/bhp-h**		
2015/15 Cum	Cummins	ISX15	2015	550	2,924	NOx:0.35	NOx:0.18	EMA
2014/14 Cum	Cummins	ISX15	2014	400 hp	2,611 mi	NOx:0.20	NOx:0.22	EMA
2011/11 Cum #1	Cummins	ISX11.9	2011	425	4,769	NOx:0.20	NOx:0.09	AQMD
2011/11 Cum #2	Cummins	ISL8.9	2011	370	2,500	NOx:0.20	NOx:0.22	AQMD
2011/11 Cum #3	Cummins	ISC8.3	2011	300	14,269	NOx:0.20	NOx:0.18	AQMD
2010/10 Cum	Cummins		2010		13,500	NOx:0.35	NOx:0.09	ARB
2014/14 DDC	DDC	DD13	2014	450	15,914	NOx:0.20	NOx:0.17	EMA
2014/14 Nav	Navistar	CXU612	2014	450	7,686	NOx:0.20	NOx:0.12	EMA
2012/12 Volvo	Volvo	MP8-415C	2012	415	12,640	NOx:0.20	NOx:0.12	EMA
2011/11 Volvo #1	Volvo	MP8-445C	2011	445	36,982	NOx:0.20	NOx:0.12	AQMD
2011/11 Volvo #2	Volvo		2011		36,900	NOx:0.20		ARB
2010/10 Volvo	Volvo		2010		68,000	NOx:0.20		ARB
		Navistar EGR only				**g/bhp-h**		
2011/11 Nav #1	Navistar	A260	2011	260	10,014	NOx:0.20		AQMD
2011/11 Nav #2	Navistar	A430	2011	430	69,500	NOx:0.20	NOx:0.43	AQMD
2011/11 Nav #3	Navistar	A475	2011	475	67,373	NOx:0.20	NOx:0.43	AQMD
2011/11 Nav #4	Navistar		2011		67,300	NOx:0.5		ARB
2010/10 Nav	Navistar		2010		70,000	NOx:0.5		ARB

The NOx emissions integrated over the hot and cold UDDS cycles for all SCR equipped engines are shown in Figure 2-37 on a brake specific engine work basis. Note the emissions factors of the 2010 Cummins, 2011 Volvo #2 and 2010 Volvo vehicles are presented on a distance specific basis, as engine work values are not available for these engines. These distance specific emissions can be divided by 3.0301 to provide an approximate comparison with brake specific engine work values using a standard conversion factor from EPA (2002). Overall, the NOx emission factors for the Cold UDDS cycles were much higher than the factors for the hot UDDS cycles. For the hot UDDS, similar NOx emission values were found for the 2015 Cum, 2014 Cum, 2011 Cum #3, 2014 Nav and 2011 Volvo #1, ranging from 0.025 g/bhp-h to 0.038 g/bhp-h, while the 2011 Cum #1 and the 2014 DDC showed much lower NOx emission factors (below 0.014 g/bhp-h). The highest NOx emissions were found for the 2012 Volvo vehicle. The fact that the 2011 Volvo #1 equipped engine has a newer model year, lower mileage and lower maximum power, but a much higher NOx emission factor than that for 2012 Volvo suggests that there might be something wrong Volvo #1 vehicle. No additional information is available about the condition of that vehicle, however. The

NOx emission factors for the hot UDDS cycles for most of tested vehicles exceeded their EPA standards shown in Table 2-1, except for the 2011 Cum #1 and 2014 DDC vehicles. For the emission factors on a specific distance base, the emission factors were found 1.98 g/mi and 1.947 g/mi for the 2011 Volvo #2 and the 2010 Volvo, respectively, while the 2010 Cum showed a much higher emission factor with the number of 3.731 g/mi. These values would convert to 0.657 g/bhp-hr to 1.231 g/bhp-hr using the emissions conversion factor of 3.031, which are generally higher than the other values.

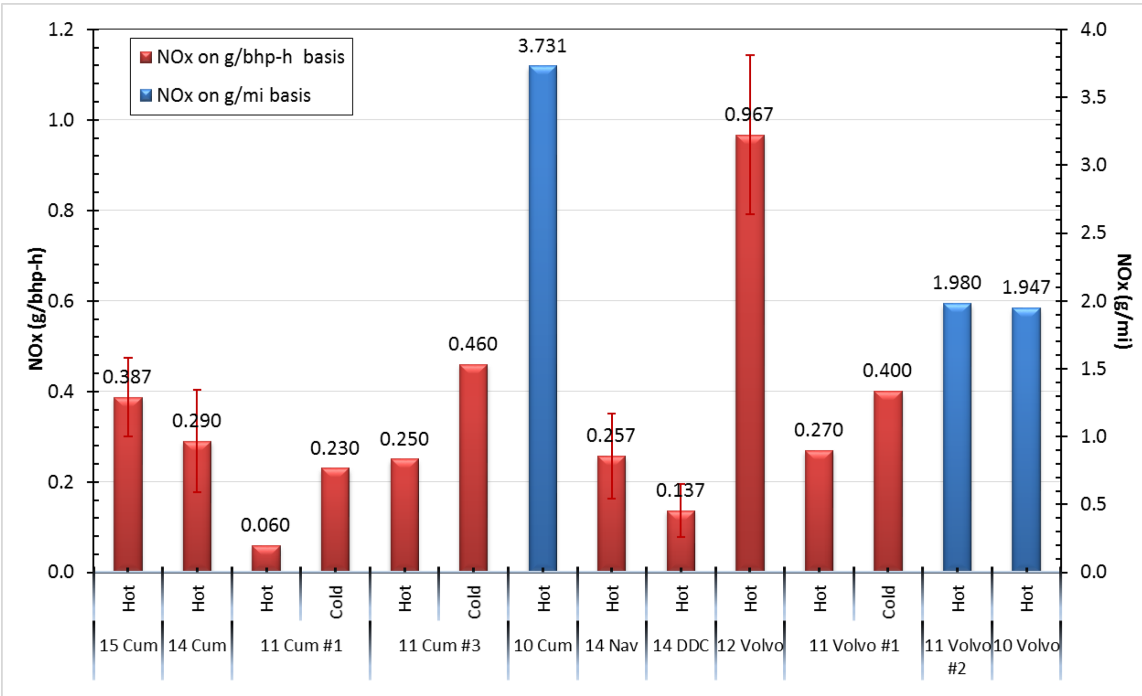


Figure 2-37 UDDS Results for 2010+ Model Year Heavy-duty Engines/Trucks (SCR-equipped)

The NOx emissions integrated over the cruise cycles for SCR equipped engines are shown in Figure 2-38 on a brake specific engine work basis. The Cruise 55 and the Cruise 65 represent the average speeds of the 55 miles/hr and 65 miles/hr reached during the main portion of the cycles, respectively. Note the emissions factors of the 2010 Cummins and the 2010 Volvo vehicles are shown on a distance specific basis. The NOx emission factors of all the tested vehicles for both the Cruise 55 and the Cruise 65 met the EPA 2010 standard with the 20% in-use measurement allowance, except for the 2012 Volvo vehicle for the Cruise 55 cycle. Generally, the NOx emission factors of the vehicles with the newer model years (2014 and 2015) were found to have lower emission factors than those of the vehicles with the model years of 2010, 2011 and 2012, except for the 2014 Navistar for the Cruise 55, The emission factors for the Cruise 65 were typically lower than the factors of the Cruise 55, except for the 2014 DDC, the 2010 Cummins #4 and the 2010 Volvo. The 2014 Cummins and the 2015 Cummins showed the lowest the NOx emissions, ranging from 0.023 g/bhp-hr to 0.052 g/bhp-hr, while the factors of other newer model vehicles (2014 DDC and the 2014 Navistar of the Cruise 65) ranged from 0.069 g/bhp-hr to 0.078 g/bhp-hr. The highest NOx emission factors were found from the 2012 Volvo, with an emissions factor of 0.257 g/bhp-hr. For the emission factors on a distance specific basis, the NOx emissions of the 2010 Cummins at 0.601 g/mi and 0.744 g/mi were almost three times more than the factors of the 2011 Volvo #2, which were 0.19 g/mi and 0.27 g/mi for the Cruise 55 and the Cruise 65, respectively, while there is an opposite trend of the emission factors on a brake specific engine work basis between the newer model year Cum engines (2014 and 2015) and the newer model year Volvo engine (2012). These values would convert to 0.199 g/bhp-hr and 0.245 g/bhp-hr for the Cruise 55 and the Cruise 65 of the 2010 Cum, respectively, and 0.063 g/bhp-hr and 0.089 g/bhp-hr for the Cruise 55 and the Cruise 65 of 2010 Volvo, respectively, using the emissions conversion factor.

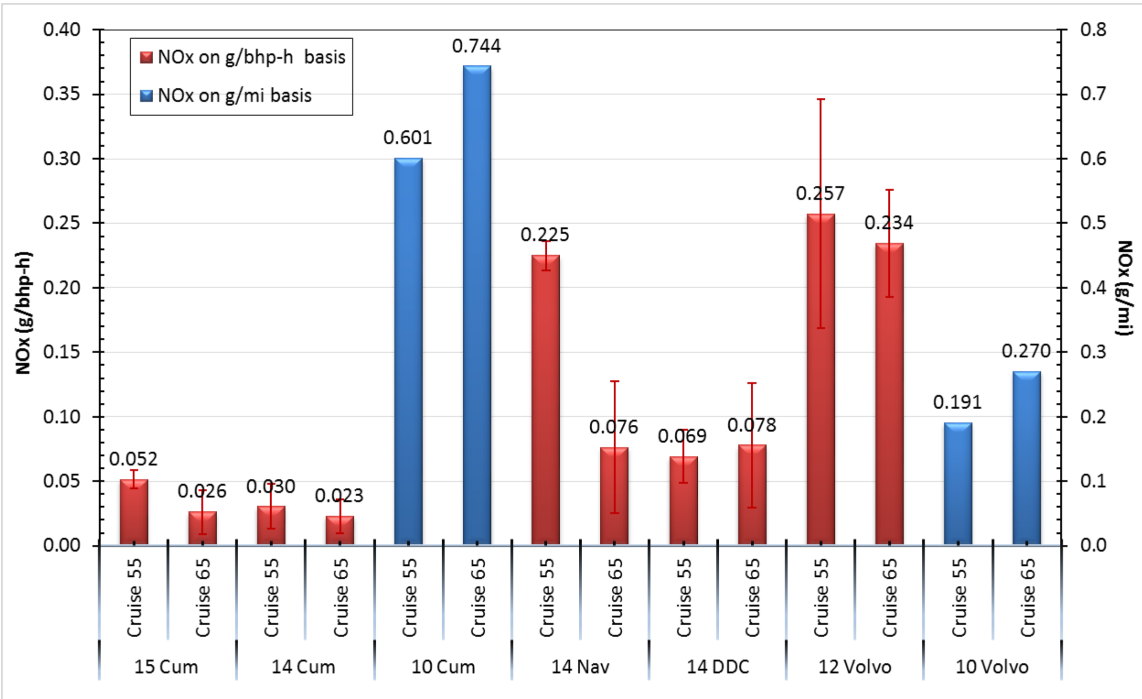


Figure 2-38 Cruise Results for 2010+ Model Year Heavy-duty Engines/Trucks (SCR equipped)

NOx emissions integrated over the port cycles with SCR equipped engines are shown in Figure 2-39 on a brake specific engine work basis. The port cycles consist of three different cycles representing Near Dock, Local and regional driving. Overall, the highest NOx emissions were found for the Near Dock cycles, while the lowest were found for the regional cycles. There were larger differences in NOx emissions over the same port cycles between the different manufacturers. For the Near Dock cycles, the 2011Volvo #1 showed the highest NOx emission factor of 1.81 g/bhp-hr, which was eight times higher than that of the 2011 Cum #1. Both of the tested vehicles were built in 2011 with the similar maximum powers (415 hp and 445 hp). The vehicles did differ in mileage, however, with the 2011 Cum #1 having a mileage under 5,000 miles, while the 2011 Volvo #1 had a mileage of almost 40,000 miles. Although deterioration may be a factor in the emissions differences between the engines, it is more likely that the differences are attributable to differences in engine/aftertreatment design.

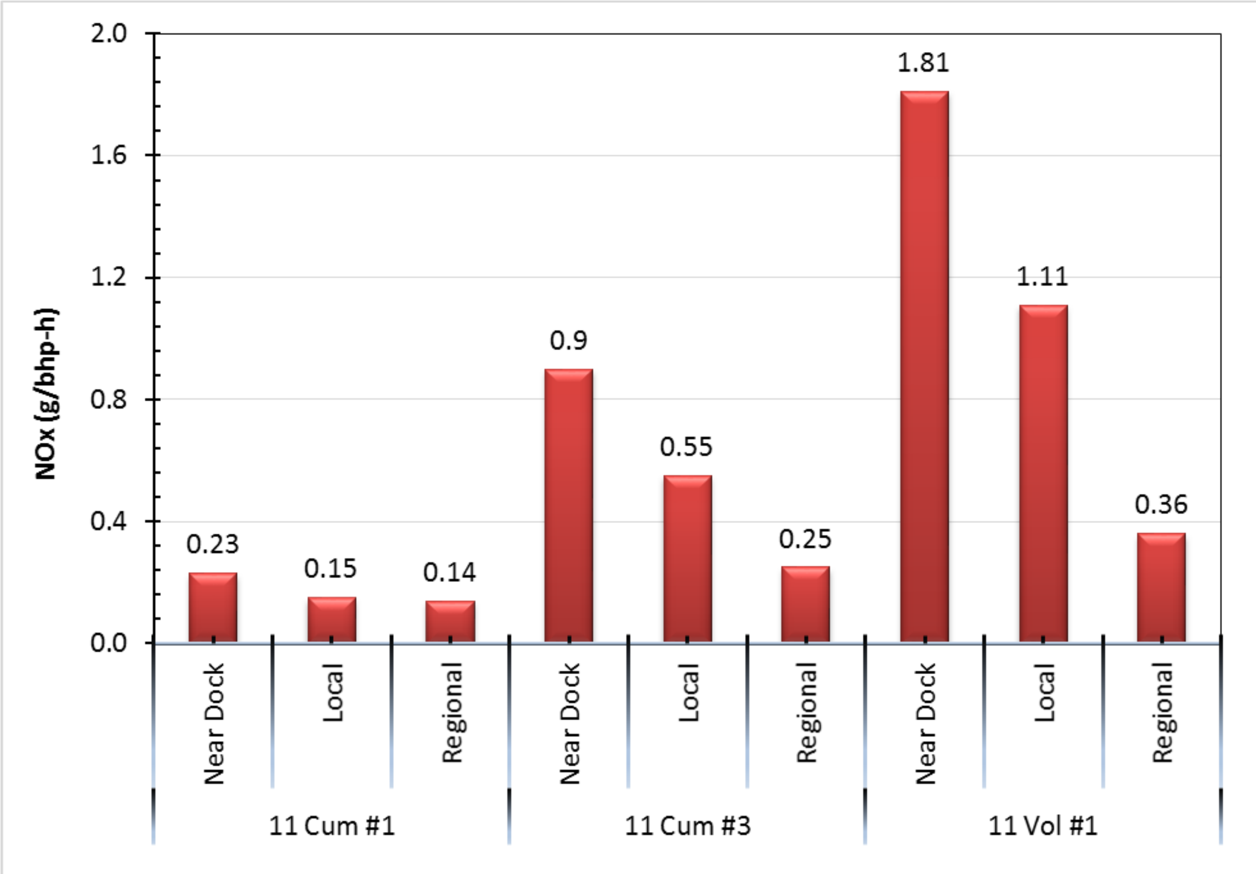


Figure 2-39 Port Cycles Results for 2010+ Model Year Heavy-duty Engines/Trucks (SCR equipped)

NOx emissions integrated over the UDDS cycles with the Navistar EGR equipped engines are shown in Figure 2-40 on a brake specific engine work basis. All the Navistar vehicles with 2010 and 2011 model years in Figure 2-40 employed only EGR and no SCR to control NOx emissions. The 2011 Nav #1, with the lowest mileage, showed the lowest NOx emissions among the five vehicles. The NOx emission factors of the 2011 Nav #3 were 1.15 g/bhp-h and 1.49 g/bhp-h for the hot UDDS and the cold UDDS, respectively, which were a litter higher than the factors of the 2011 Nav #2. As discussed earlier, the NOx emission factors for the SCR equipped engines ranged from 0.06 g/bhp-h to 0.39 g/bhp-h for the hot UDDS cycles and from 0.23 g/bhp-h to 0.46 g/bhp-h for the cold UDDS cycle. The Navistar vehicles with EGR showed almost five times higher NOx emissions than the vehicles with SCR, except for the 2011 Nav #1 vehicle. For the emission factors on a specific distance basis, the 2011 Nav #4 with the newer model year and lower mileage had a lower NOx emission factor than that of the 2010 Nav. These values would convert to 1.818 g/bhp-hr and 1.391 g/bhp-hr using the emissions conversion factor of 3.031.

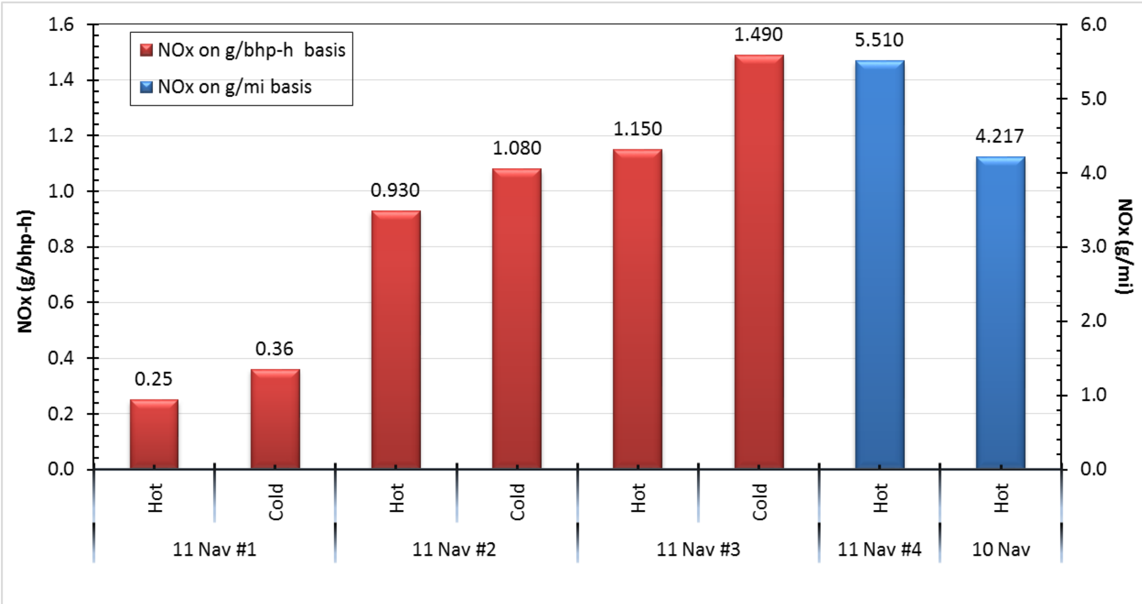


Figure 2-40 UDDS Results for 2010+ Model Year Navistar EGR ONLY Heavy-duty Engines/Trucks

2.2.2 In-Use Studies

As part of the SCAQMD chassis dynamometer study, WVU also characterized emissions from a heavy-duty diesel truck equipped with a DPF and SCR during a long-haul operation across the country (Carder et al., 2014). A 2011 Mack truck was used to transport WVU's transportable emissions measurement system (TEMS) across the country while continuously measuring emissions through a 40 CFR Part 1065 compliant CVS system for over 2500 miles. The entire test route, designated in different color representing different test days, along with the stops demarcating micro-trips is illustrated in Figure 2-41. The trace of altitude change with distance for the entire test route is shown in Figure 2-42. The vehicle was instrumented to monitor NOx and PM emissions performance and conduct a thorough analysis of the effect of road-grade on real-world emissions rate. Results of the cross-country study showed that the NOx conversion efficiency of the SCR after-treatment system to be on an average 83-88% during the course of the test campaign. Sustained temperatures of greater than 250°C contributed to high SCR activity at highway driving conditions. The brake specific NOx emissions were higher than certification standards by an order of magnitude at high altitudes, greater than 1524 m (5000 ft), due to engine protection strategies adopted to overcome the operational limitations encountered at high altitudes, and also due to the fact that engine manufacturers are exempted from complying with NOx emissions standards at high altitudes greater than 5500 feet above sea level. There was also a particular "high NOx" event that observed in the state of Kansas where high NOx emissions were observed in conjunction with exhaust temperatures in the range of 450°C. It was suggested that this might be attributable to an aftertreatment maintenance strategy to burn adsorbed hydrocarbons, prevent urea crystallization, and regenerate the active surfaces of the SCR through addition of exhaust energy.

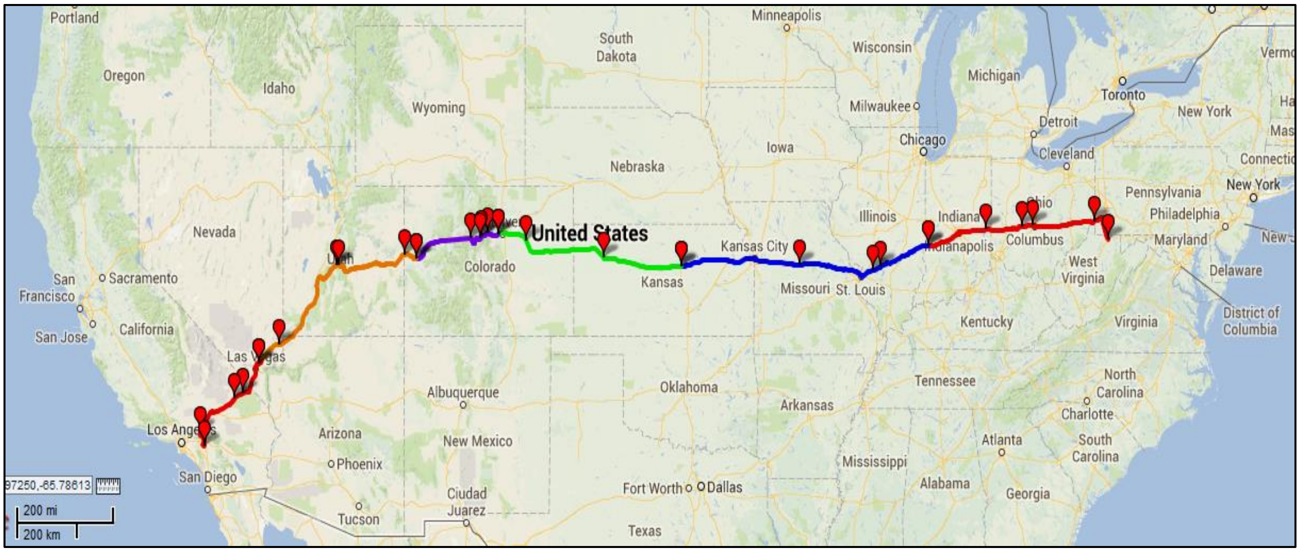


Figure 2-41: Entire Test Route with Stop Indicators

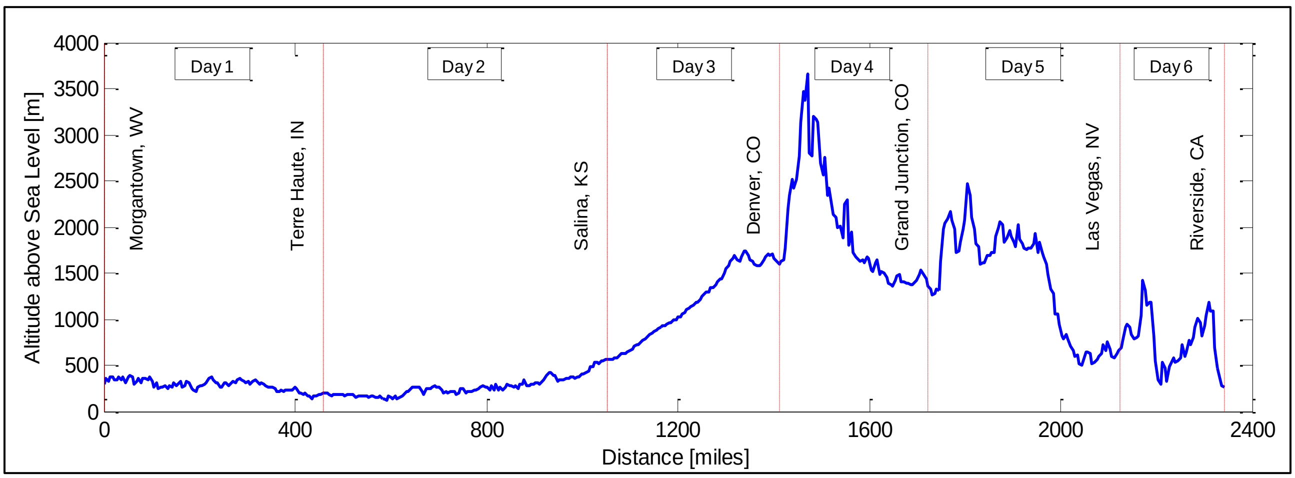


Figure 2-42: Altitude Trace of the Complete Test Route

WVU conducted an extended testing study of MY 2014 Class 8 trucks fueled by diesel and natural gas in Southern California, under funding from CARB and the SCAQMD (Thiruvengadem et al., 2016). The results from this study provide a assessment of in-use compliance of four major OEM's in heavy-duty truck applications. The study involved more than 1200 miles of on-road testing for each test vehicle. The study was unique in that it used 3 different PEMS instruments and a transportable CVS emissions measurement system (TEMS). For an extended freeway type of operation the average brake-specific NOx emissions for SCR equipped trucks from all the four OEMs were found to be 0.22 g/bhp-hr with a standard deviation of 0.18 g/bhp-hr. Over the same operation, a lowest brake-specific NOx emissions of 0.094 was observed, while the highest brake-specific NOx emissions was observed to be at 0.67 g/bhp-hr. For a driving route that simulated inside port operation, the average brake-specific NOx emissions of all four OEM was found to be 0.99 g/bhp-hr with a standard deviation of 0.41 g/bhp-hr. The inside port operation was characterized by extended idle times, with all vehicles idling for an average of 50% of the total duration of the trip. The brake-specific NOx emissions from the CNG truck were 69% and 88%

lower than the average of the SCR equipped trucks over the freeway and inside port operation, respectively.

CARB has on-going efforts to evaluate the emissions of heavy-duty trucks under on-road conditions. This includes testing programs being conducted in both Southern and Northern California. For the Northern California studies, Misra et al. (2013) undertook a study to characterize the in-use emissions of model year (MY) 2010 or newer diesel engines. Emissions from four trucks: one equipped with EGR only and three equipped with EGR and SCR were measured on two different routes that included a cold start, an arterial, highway driving, and industrial driving with three different payloads in the Sacramento area using a PEMS. Results indicated that brake-specific NOx emissions for the truck equipped only with an EGR were independent of the driving conditions. The three EGR + SCR trucks included ones equipped with a 2010 Cummins ISX engine, a 2010 DDC D-13 engine, and a 2010 Volvo D-13 truck. The results for these three trucks are shown in Figure 2-43, Figure 2-44, and Figure 2-45, respectively. Results also showed that for typical highway driving conditions, the SCR technology was effective in controlling NOx emissions, with emissions rates in the range of 0.07 to 0.10 g/bhp-hr. However, under operations where the SCR’s do not reach minimum operating temperature, like cold starts and some low load/slow speed driving conditions, NOx emissions are still elevated. NOx emissions ranged from 1.59 to 3.04 g/bhp-hr for the cold starts and from 0.32 to 1.04 g/bhp-hr for the arterial driving, with the DDC D-13 showing the lowest emissions while the Volvo D-13 showed the highest emissions. NOx emissions for the industrial driving showed lower emissions of 0.17 to 0.24 g/bhp-hr for portions of the industrial cycle where the exhaust temperature was sufficiently high for the SCR to operate. The Cummins ISX and Volvo D-13 both showed increases in NOx emissions of 3.39 to 3.74 g/bhp-hr for industrial driving, however, when temperature of the SCR catalyst dropped below the 200°C. Note that the exhaust temperature for the Cummins engine, with a copper-zeolite SCR catalyst, dropped below 200°C shortly after the truck exited the highway, whereas the exhaust temperature for the Volvo D-13, with an iron-zeolite SCR catalyst, only dropped below 200°C after extended industrial driving.

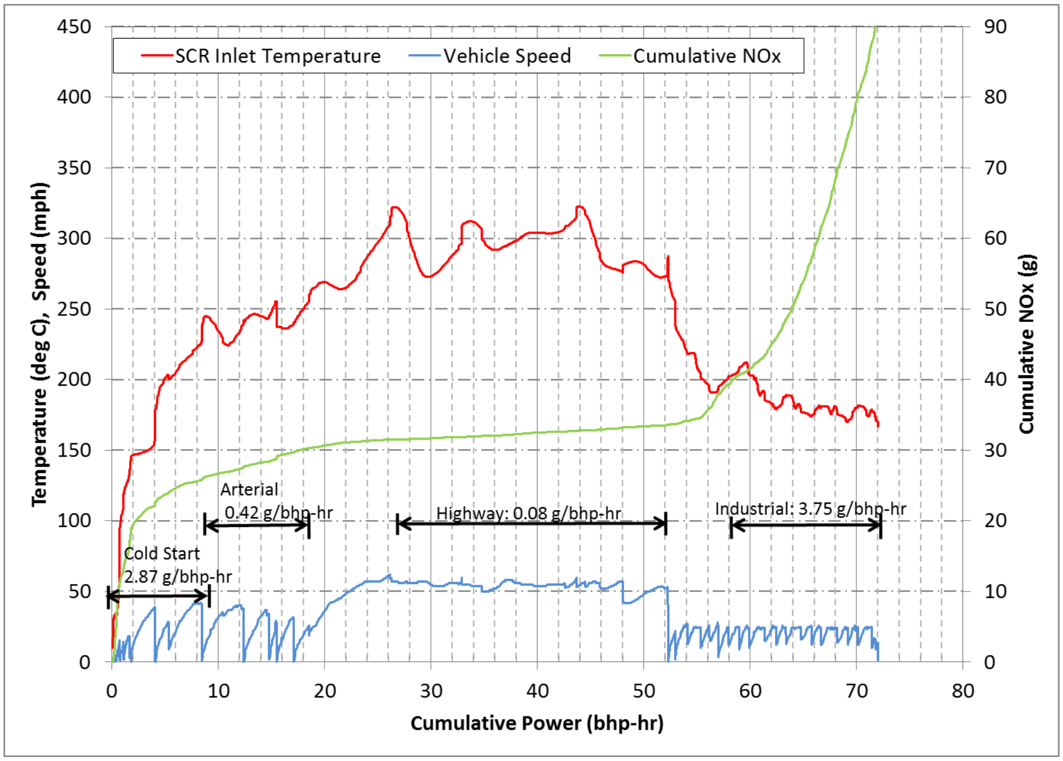


Figure 2-43. In-use Emissions for a 2010 Cummins ISX equipped Truck

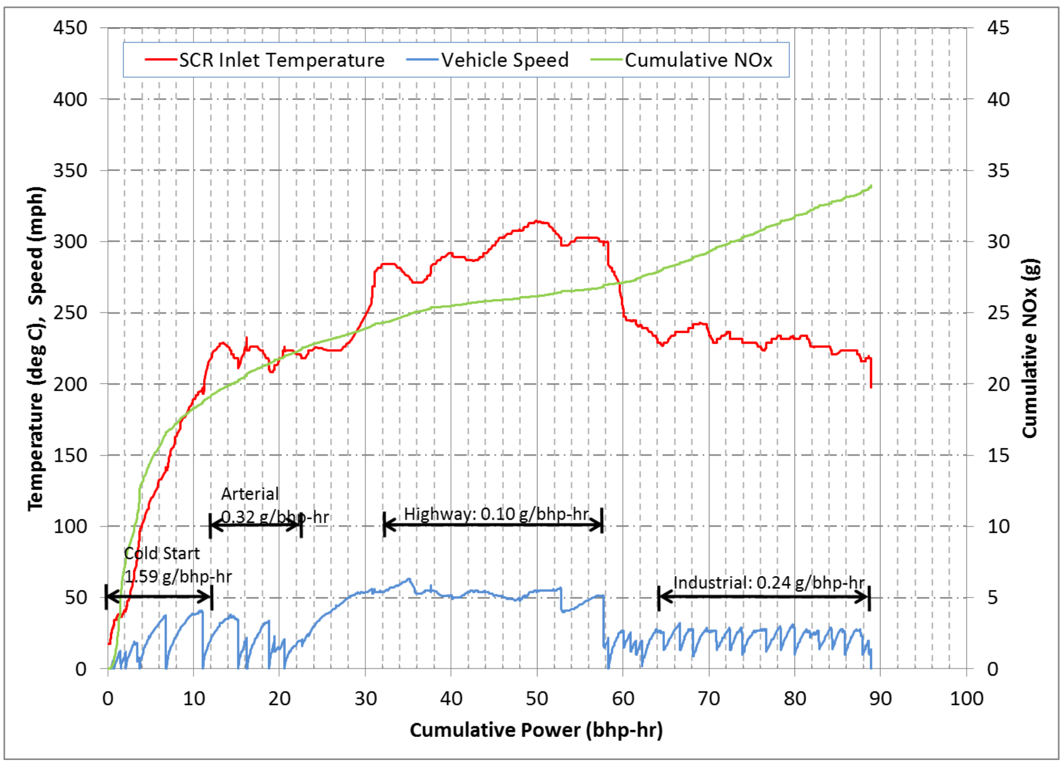


Figure 2-44. In-use Emissions for a 2010 DDC D-13 equipped Truck

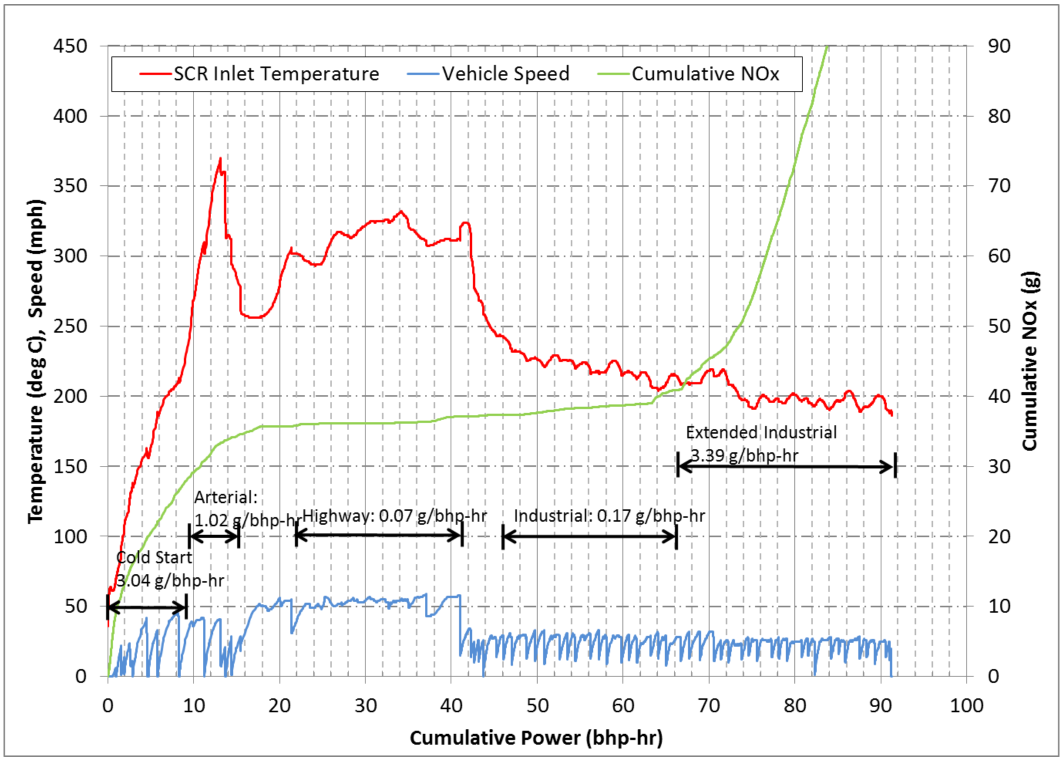


Figure 2-45. In-use Emissions for a 2010 DDC D-13 equipped Truck

In a follow up study in Northern California, additional tests were conducted on (i) a 2011 Detroit Diesel Corporation DD-13 engine that was tested under a previous program in 2012 and (ii) on the newest and lowest certified engines for each of three prominent manufacturers - Detroit Diesel, Volvo and Cummins (Misra et al., 2016). The testing of the aged 2011 DDC DD-13 (cert: 0.13 g NOx/bhp-hr; 138,000 Miles) showed almost no deterioration compared to the tests conducted at 23,000 miles, as shown in Figure 2-46. The highway and the low-load slow-speed NOx emissions for the low mileage tests were 0.16 g NOx/bhp-hr and 0.26 g NOx/bhp-hr, respectively, while these values for the high mileage tests were 0.17 g NOx/bhp-hr and 0.23 g NOx/bhp-hr, respectively. The thermal management on the 2011 DDC DD-13 was very effective, showing consistent diesel exhaust fluid (DEF) injection during the low load slow speed driving (~20 miles). Similar performance was observed for arterial stop-and-go driving (~5 miles) where DEF injection and NOx emissions well below the 2010 NOx standard were observed for a majority of the tests. Results also indicated that while the majority of NOx emissions occurred during the cold start, DEF injection started within half a mile after a cold start contributing to emissions reductions even during the arterial driving that followed. The average DEF-to-fuel ratio for all tests was between 1.3-1.4 percent by volume. During these tests, the 2011 DDC DD-13 was also shown to have sustained thermal management for prolonged low load slow speed driving, which was found to be superior than a 2010 Volvo D13-H (cert: 0.11 g NOx/bhp-hr) that was tested under a previous program. The 2010 Volvo D13-H was unable to sustain NOx reductions during prolonged low load slow speed operation, unlike the 2011 DDC DD-13, although the highway NOx emissions for 2010 Volvo D13-H are far lower (~0.05 g NOx/bhp-hr) for the identical payload and route. Testing was also conducted on a 2014 DDC DD-15 (cert: 0.09 g NOx/bhp-hr), as shown in Figure 2-47. Interestingly, the 2014 DDC DD-15 was found to have worse thermal management than the 2011 DDC DD-13, leading to higher NOx emissions, particularly at low load. A 2014 Volvo D13-J (cert: 0.06 g

NOx/bhp-hr) was also tested, as shown in Figure 2-48, and compared against a 2010 D13-H that was tested previously. It was found that the 2014 Volvo D13-J had lower SCR inlet temperatures at the onset of driving as well as higher arterial and highway NOx emissions compared with the 2010 Volvo D13-H. It was also found that the DEF injection stopped shortly after starting the industrial driving for the 2014 Volvo D-13, with NOx emissions increasing once the stored NH_3 is depleted.

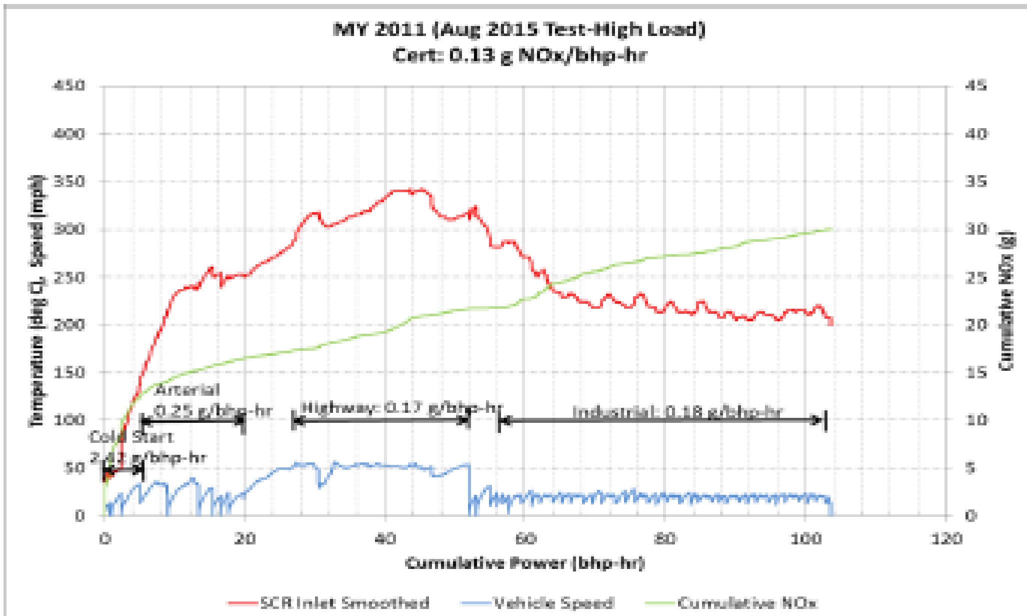


Figure 2-46. In-use Emissions for a aged 2010 DDC D-13 equipped Truck

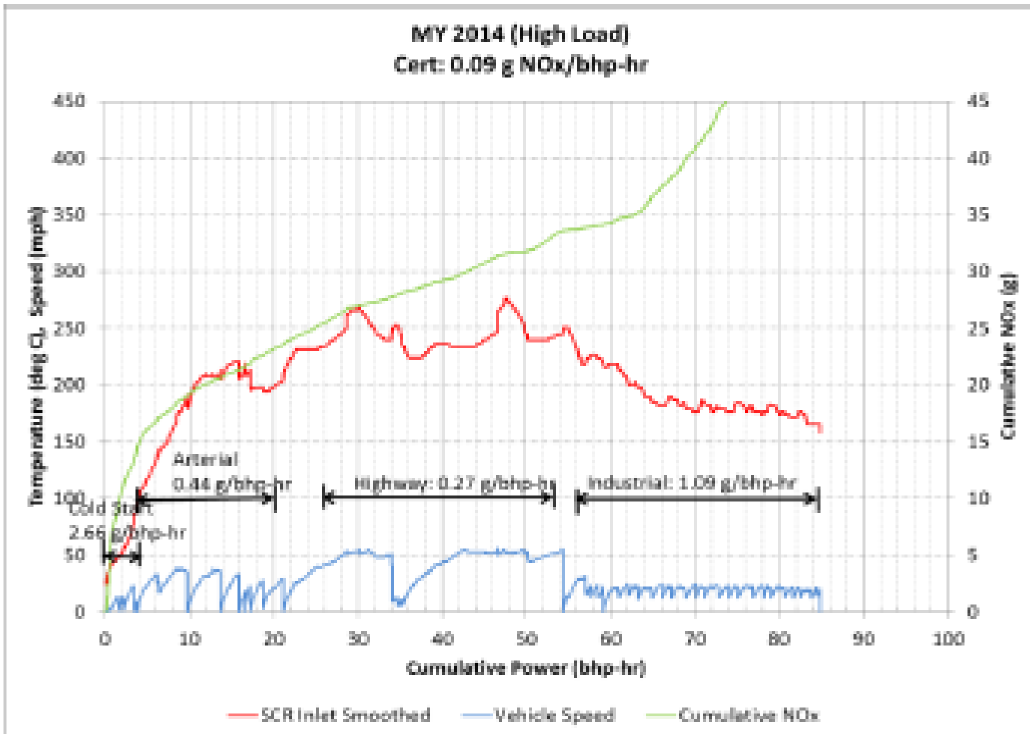


Figure 2-47. In-use Emissions for a 2014 DDC D-13 equipped Truck

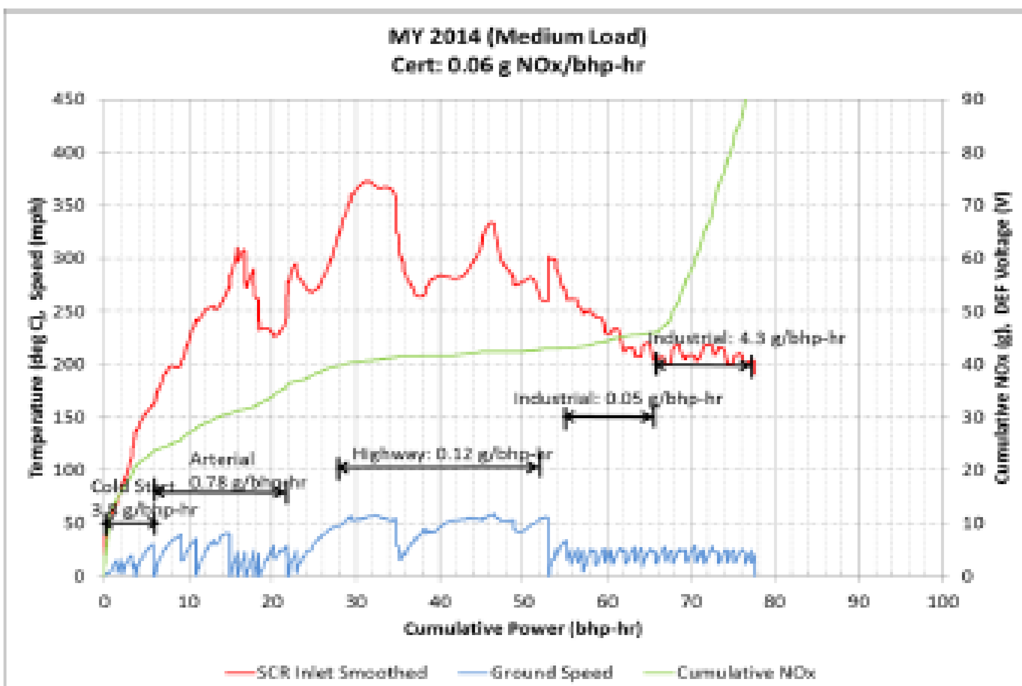
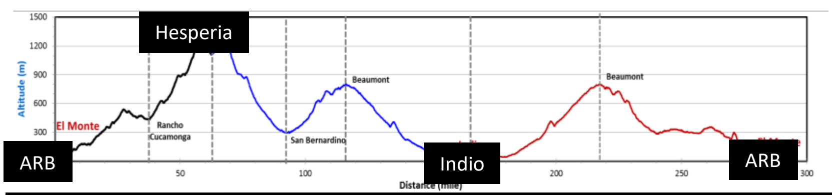


Figure 2-48. In-use Emissions for a 2014 Volvo D-13 equipped Truck

CARB has also been conducting heavy-duty in-use compliance (HDIUC) testing in Southern California pursuant to Title 13, California Code of Regulations, Sections 2111-2140 (O'Cain et al., 2016, Tu et al., 2016; Lee et al., 2017; O'Cain et al. 2018). To date, CARB has tested approximately 23 vehicles (O'Cain, 2018). This testing has focused on three engine families. For the three families, 6 of 10 vehicles were found to be noncompliant with the NTE standards for one engine family, with an average NTE emission rate of 0.59 g/bhp-hr, and 8 of 10 vehicles were found to be noncompliant for the second engine family, with an average NTE emission rate of 1.02 g/bhp-hr. To date, the test results for the third engine family are in compliance with the in-use emissions limits. Additional steady state chassis dynamometer and engine testing is also being conducted in conjunction with this testing.

More detailed results for some of the earlier test vehicles and different test routes are shown below in the Table 2-10, along with the altitude for each the route. The first route was a 130 mi travel from El Monte to Hesperia and then a return trip back to El Monte. The second route was a 245 mi travel from El-Monte to Indio and then a return trip back to El-Monte. The third route was a 290 mi travel from El-Monte to Hesperia and then passed through Indio before heading back to El-Monte. There were three trucks that were involved in this study, a 2013 Navistar, which was tested over all three routes, a 2014 DDC, which was tested over Route 1 and Route 2, and a 2013 Volvo, which was tested over Route 3 only.

Table 2-9 Test Routs Information for CARB in-use Studies



Route ID	Route	Truck #1	Truck #2	Truck #3
Route 1 /130mi	El Monte - Hesperia -El Monte	*	*	
Route 2 /245mi	El Monte - Indio -El Monte	*	*	
Route 3 /290mi	El Monte-Hesperia - Indio - El Monte	*		*
Truck #4,5,6 and7 used routes: ARB Depot Park Lab-Placerville (PL) and ARB Depot Park Lab-West Sacramento (WS)				

NOx emissions integrated over all the test routes for each truck for the Southern California testing are shown in Table 2-11, showing the total NOx emissions for each truck on a gram brake horsepower hour basis. For the 2013 Navistar, there was a total of 133 grams of NOx emitted over the three different test routes, with 125 grams emitted outside of the NTE Zone and 8 grams emitted in the NTE Zone. There were 6 NTE events that were happened over the three test routes, which included at least a 30 second in the NTE region as well an SCR temperature higher than 250 °C. For the 2014 DDC, there was a total of 180 grams of NOx emitted over test routes 2 and 3, with 171 grams emitted outside the NTE Zone and 9 grams emitted in the NTE Zone. There were an average of 0.4 NTE events that occurred over the three test routes. For the 2013 Volvo, there was a total of 50 grams of NOx emitted over test route 3, with 46 grams emitted outside the NTE Zone and 2 grams emitted in the NTE Zone. There was 1 NTE event that happened over the three routes of testing.

Table 2-10 NOx Emissions of NTE and MAW Requirements (El Monte)

Manufacturer	13 Navi	14 DDC	13 Vol
Total NOx /g	133	180	50
Non-NTE Zone NOx /g	125	171	46
NTE Zone NOx /g	8	9	2
NTE Event (>= 30sec & 250C) NOx /g	6	0.4	1

NOx emissions the full route or various subsets of the full route were generally in the range of 0.100 to 0.500 g/bhp-hr. The results showed that emissions varied for different segments of the route and for different vehicles, with emissions on a g/bhp-hr basis being sometimes higher for the downhill portions of the route. In-use emission rates for different segments of driving for two of the trucks are shown in Figure 2-49 and Figure 2-50.

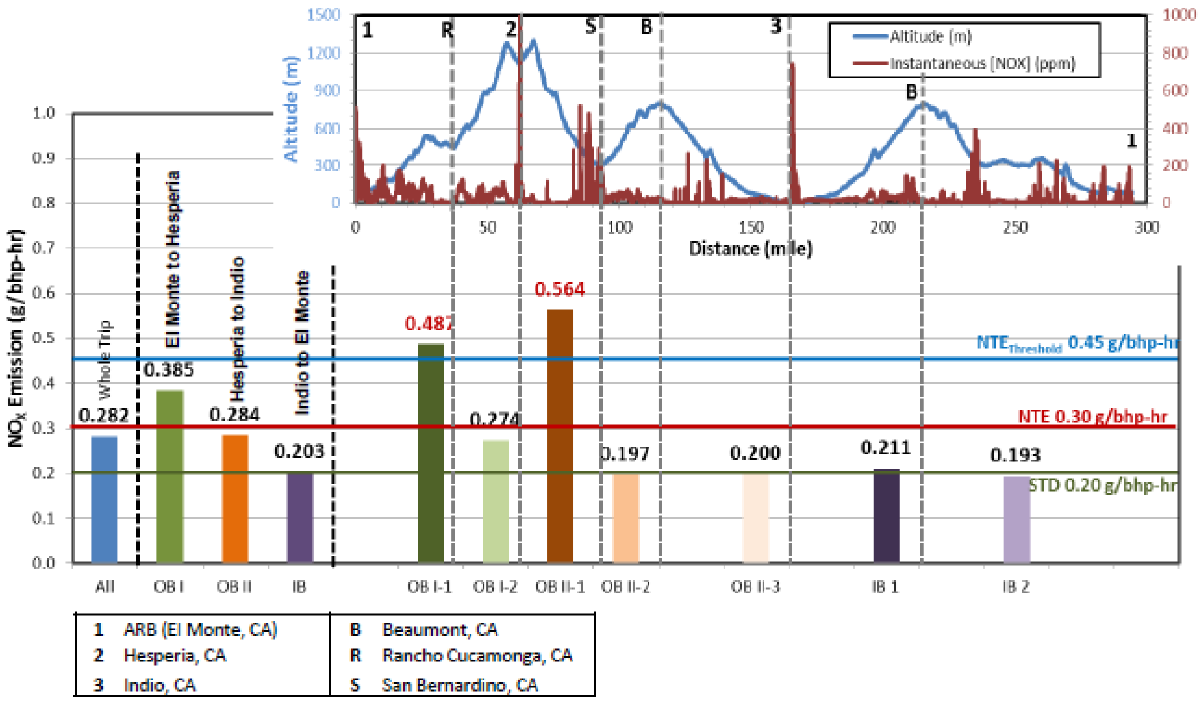


Figure 2-49. In-use NOx emissions for 2013 Truck over a Route from El Monte to Hesperia to Indio and Back to El Monte

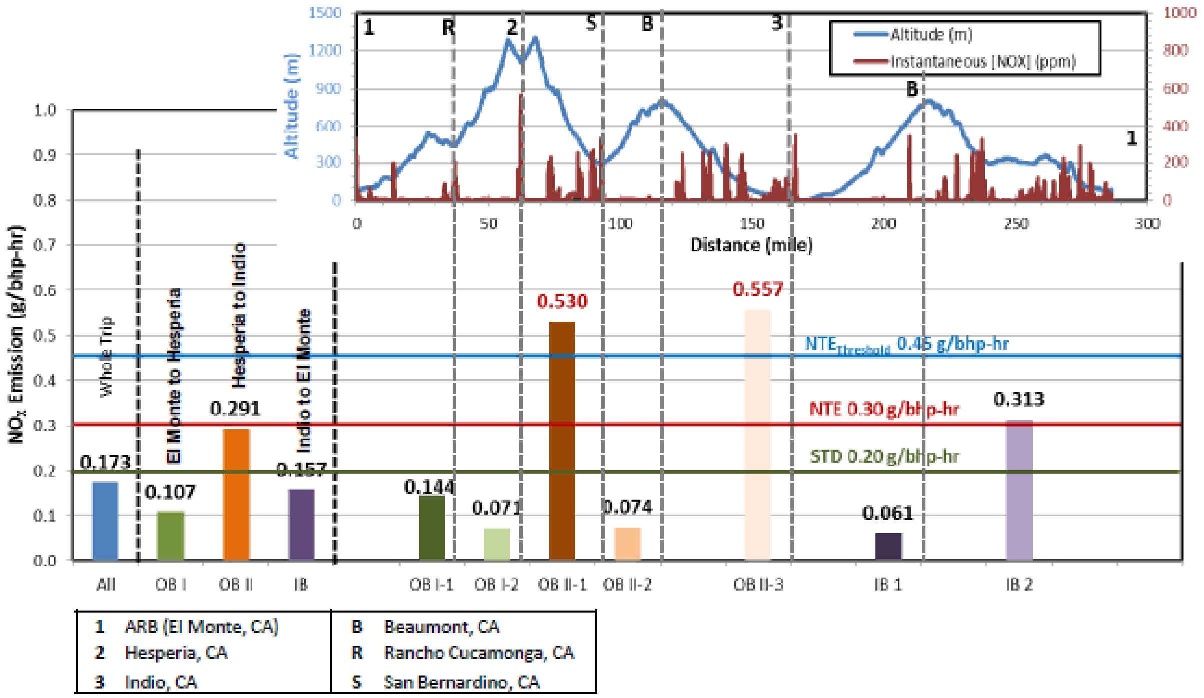


Figure 2-50. In-use NOx emissions for 2013 Truck over a Route from El Monte to Hesperia to Indio and Back to El Monte

Yoon et al. (2016) have conducted additional analyses to better understand the differences between NOx certification standards and in-use NOx emissions and if these differences are being effectively captured by the in-use compliance methods. They evaluated the in-use emissions for one of the 2013 trucks testing on the El Monte – Hesperia – Indio route. For this truck, they found that 81% of the activity was not in the NTE zone, representing 94% of the total trip NOx emissions. Another 19% of the activity was in the NTE zone, but did not meet the criteria in terms of event duration being greater than 30 seconds or aftertreatment temperature being above 250°C. Only 12% of the activity met the criteria for an NTE event, representing only 5% of the total trip NOx emissions. Under these conditions, the truck passed the NTE in-use testing requirements. Using the MAW, 54% of the MAW were found to be valid, based on an average power being greater than 20% of the maximum engine power. Of the valid MAWs, 94% of the windows were below the 1.5 conformity factor, thus the vehicle also passed the in-use testing requirements, which requires that >90% of the valid MAWs have a conformity factor below 1.5. On the other hand, the NOx emissions on a g/bhp-hr basis for the invalid MAWs were more than 6 times higher than those for the valid MAWs, indicating that a significant portion of the in-use NOx emissions might be generated under conditions not covered by the MAW method. Similar results were also found for a second truck over a similar route, with only 5% of the activity meeting the requirements for a valid NTE event, while 55.3% of the activity was valid MAWs, with 96.8% of these meeting the 1.5 conformity factor. The emissions for the invalid MAWs were more than 14 times greater than those for the valid MAWs. Finally, they evaluated the activity for a truck driving in the Sacramento area under lower power conditions typical of urban vocational trucks. This truck trips showed only 1% of the data meeting the criteria for an NTE event and none of the MAW meeting the criteria that the average power was greater than 20% of the maximum engine power, making it an invalid MAW test.

The establishment of the heavy-duty in-use testing (HDIUT) program has also provided extensive data sets of in-use emissions of heavy-duty trucks. To date this has included data from up to 300 2010+ trucks. Sandhu et al. (2018) evaluated HDIUC data from over 170 trucks as a function of different speed and power bins. For vehicles certified to the 0.2 g/bhp-hr standard, NOx emissions were found to increase from 0.24 g/bhp-hr to 1.4 g/bhp-hr as speeds decreased from 50 to 90 mph to 2 to 25 mph. They found emissions were a strong function of the aftertreatment temperature, with higher emissions when the aftertreatment temperature was below 250°C in comparison with conditions when the aftertreatment was above 250°C. They also found some trends of lower emissions for 2013-2014 MY vehicles in comparison with 2011-2012 MY vehicles. Spears et al. (2018) also evaluated emissions 122 HDVs collected as part of the HDIUT program. They separated the vehicles into a ‘credit’ group, where engines were produced at higher certification levels using provisions with banked credits, and a ‘non-credit’ group. The results showed that the vehicles of the ‘non-credit’ group had an average NO_x emission rate of 0.37 g/bhp-hr, compared with 0.70 g/bhp-hr of the vehicles with the emission credit, which indicates that it is important to separate certification categories for vehicles when reporting the real world NO_x emission rates.

The incorporation of NOx sensors into the standard configurations for SCR-equipped engines has provided an additional source of information about in-use NOx emissions. Howard et al. (2018) showed good performance for NOx sensors in comparison with measured NOx values under conditions where the exhaust temperatures and flow rates were sufficiently high (e.g., High-Speed Cruise, Cruise cycle, and UDDS). The NOx sensor performance was more uncertain under low SCR temperature conditions and for low exhaust flow rates because the NOx sensor goes to sleep when the SCR is cold (i.e., <190°C) and mass air flow rates have more uncertainty. Tan et al. (2018) also evaluated the NOx emission rates from the activity data of CE-CERT’s dataset. They found that high NOx emissions were still a common problem in the real world heavy-duty diesel fleet, primarily due to low SCR conversion efficiencies, low SCR temperatures, and potentially malfunctioning SCRs. The results showed that the NOx conversion efficiencies of 57 out of 67 were lower than 80% when the SCR inlet temperature was lower than 200℃. Twenty eight trucks also had NOx conversion efficiencies below 80% when the SCR inlet temperature was above 250℃. Spears et al. (2018) also evaluated this same data set. They separated the vehicles into ‘credit’ and ‘non-credit’ groups by using if engine family has banked emissions credit. For this data set, the results showed average emissions of 0.33 g/bhp-hr for the ‘non-credit’ group and 1.02 g/bhp-hr for the ‘credit’ group. They also conducted some additional analyses where the data were weighted based on EMFAC breakdowns of VMT fraction for different types of driving, as one focus of the collected data set was to look at lower load operation. With VMT weighting, the results for the results for the ‘non-credit’ and ‘credit’ engines became 0.23 and 0.70 g/bhp-hr, respectively. As discussed above, an important limitation of this data set was that NOx emissions below 190°C were not captured, and hence important regions of higher NOx emissions were not included in the analysis.

Other methodologies have also been utilized to evaluate to evaluate in-use emissions of heavy-duty trucks. Remote sensing is a technique that has been widely used to characterize emissions from light duty vehicles. This technique has now been more widely applied to heavy-duty vehicles. Some of the early studies of heavy-duty vehicles with RSD were done before the more widespread implementation of DPF and SCR aftertreatment systems in 2007 and 2010, respectively, and are less relevant in terms of the goals of the present study (Burgard et al., 2006). More recently, RSD has been used to characterize the impacts of programs implemented at the ports of Los Angeles (LA) and Long Beach to accelerated the implementation of trucks meeting 2007 standard for all port activities. This study also involved testing at a truck stop in more suburban area of LA (Peralta). RSD studies were carried out in 2008, 2009, 2010, and 2012. The results are presented in Figure 2-51. For the measurements between 2008 and 2010, the LA port facility showed reductions of 54% and 48%, respectively, for opacity and NOx emissions for truck using the port facilities, along with a 20 fold increase in NH_3 emissions due to the increase deployment of stoichiometric natural gas trucks (Bishop et al., 2012). The results also showed progressively lower NOx emissions of 12% for the port location and 18% for the port site, consistent with the implementation of 2010-compliant SCR-equipped trucks (Bishop et al., 2013). A closer analysis of the NOx emissions on a model year basis showed that the 2013 model year truck NOx emission rate of 2.4 g NOx/kg of fuel was approximately an 82% reduction in NOx emissions from the 2004-2007 model year trucks, although this value was still above the 1.33 g NOx/kg of fuel that would correspond to the 0.2 g NOx/bhp-hr emission standard. For the SCR-equipped truck, they also found differences in the NOx emissions between the port and the Peralta facilities, with higher NOx emissions observed for the port locations. It was suggested that differences in the exhaust temperatures led to differences in the effectiveness of the SCR between the two facilities. Infrared thermograms showed that the temperatures of the exhaust pipes at the Peralta truck stopped showed a mean of 225°C, which was 70°C higher than the ~143°C measured for the port location, consistent with the idea that the SCR systems at the port were more likely to be operating below the optimal operational temperature.

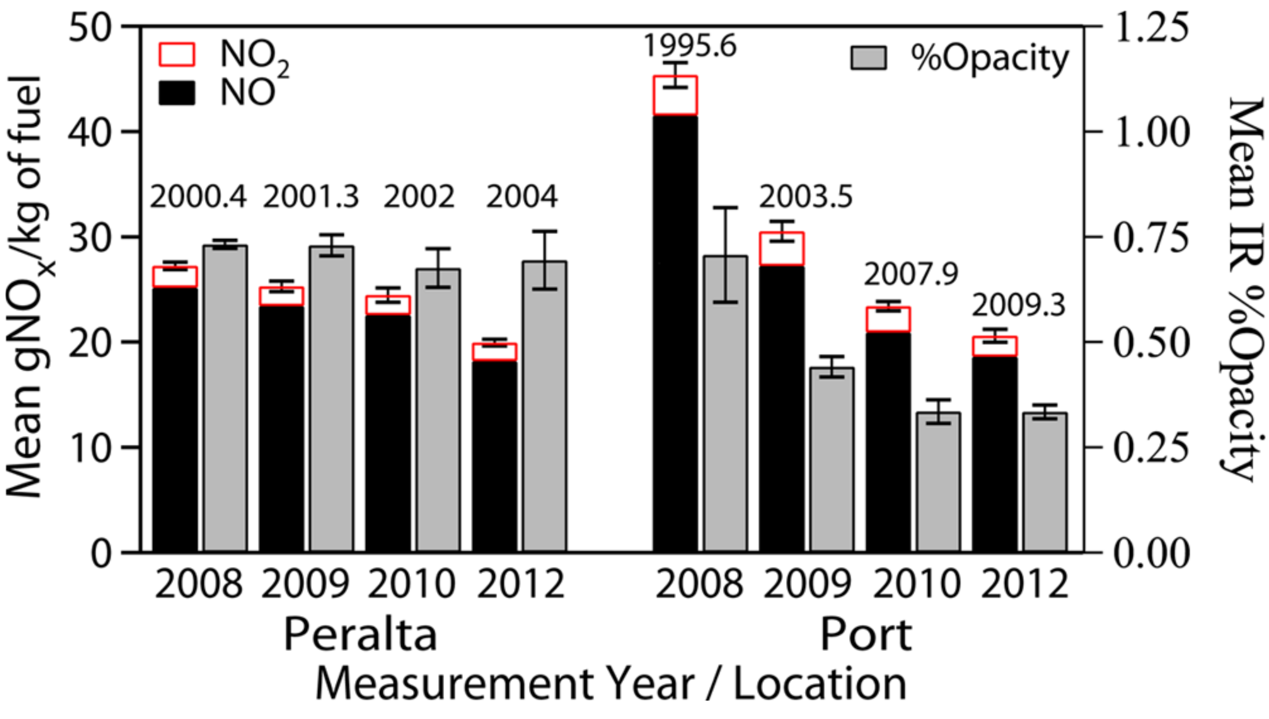


Figure 2-51. Remote Sensing Device Measurements at the Port of Los Angeles/Long Beach and at the Peralta Truck Stop.

Bishop et al. (2018) also developed an On-road Heavy-duty Measurement System (OHMS) to evaluate in-use emissions of heavy-duty trucks under roadside conditions. This method has been used to measure over 7,075 HDV emissions at the Port of Los Angeles and the Cottonwood weight scales of northern California. The results of OHMS study conducted in 2017 are presented in Figure 2-52. The results show that the NOx emissions of the Cottonwood progressively decreased for newer model year vehicles chassis, consistent with the implementation of 2010-compliant SCR-equipped trucks (Bishop et al., 2013), although this value was still above the 1.33 g NOx/kg of fuel that would correspond to the 0.2 g 2010 NOx/bhp-hr emission standard. However, the Los Angeles port facility showed an opposite trend with higher NOx emission rates for the vehicles with the chassis model years of 2016 and 2017, compared with the 2011 and 2012 chassis vehicles. After examining the exhaust tailpipe temperature, low operating temperatures (average of 86°C) were found to lead to the higher NOx emissions for the newer model year vehicles at the Los Angeles port (Haugen and Bishop, 2017). The OHMS has also been evaluated in several studies in Texas as a potential tool for a HDDV inspection and maintenance (I/M) program, where the OHMS was compared with PEMS measurements from different trucks. In the first phase of this program, showed a coefficient of determination (R^2) of 0.8081 with the PEMS, but showed a slope of 1.8044 g/kg, indicating the SHED overestimated NOx emissions relative to the PEMS (Texas A&M Transportation Institute, 2013). In the second phase of this program, the OHMS showed a closer comparison, with a percentage difference of 9.2% compared with PEMS readings (Claus et al., 2018). As part of these studies, the OHMS was also used to identify higher emitters at a Texas weight station. The high emitters identified in this part of the study represented less than 8% of the screened vehicles, but were found to contribute over one fifth of the total NOx emissions. The HDDVs were classified as higher emitters when the emission rates was higher than the 95th percentile of entire fleet.

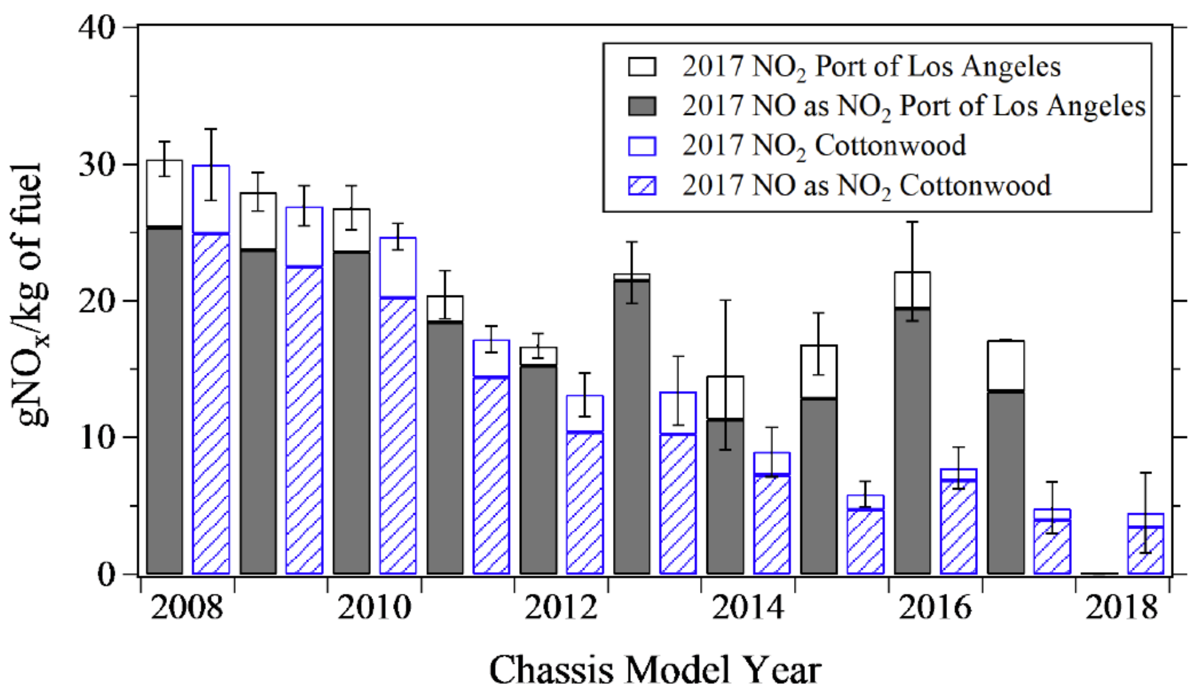


Figure 2-52 OHMS Measurements at the Port of Los Angeles and the Cottonwood Scales of northern California

In addition to RSD measurements, measurements of in-use truck emissions have also been made using measurements in traffic tunnels or freeway overpasses. An extensive series of such experiments has been carried out in the Bay area over a period extending back to the 1990s (Dallman et al., 2010, 2011, 2012, 2013, 2014). More recently, sample probes have been implemented in tunnels for the measurement of individual heavy-duty truck emissions. Although these measurements have not incorporated significant information about 2010+-compliant trucks to date, they have shown increases in the ratios of NO_2/NO emissions for newer trucks, consistent with greater number of DPF-equipped trucks being incorporated into the in-use fleet.

CARB has also developed an in-house prototype roadside plumb sampling system for HDVs called Portable Emissions AcQuisition System (PEAQS) (Ham et al., 2017; CARB, 2017, Smith, 2018). The system includes a updraft and downdraft sampling line, emissions analyzers for NOx, PM, and CO_2, and a license plate reader. The PEAQS system is designed for multiple uses, including research, regulation development and implementation, air monitoring, fleet characterization, and as an enforcement screening tool to prioritize inspections and investigations. The PEAQS system uses multiple criteria for data validation, including valid pollutant peaks co-aligned with the CO_2 peak, vehicle image captured, and valid vehicle speed. The PEAQS was used in a study in the Fall of 2016 at a California Department of Food and Agriculture (CDFA) Inspection Station in Truckee, CA. A total of 700 HD trucks were measured during this study, including 429 with updraft exhausts and 271 with downdraft exhausts. The results showed that high emitters contributed disproportionately to the total fleet emissions, with 48 of the 700 vehicles emitting 50% of the total NOx, and 21 of the 700 vehicles emitting 50% of the BC.

2.2.2.1 Summary Results for In-Use Emissions Studies

This section summarizes the results from the CARB in-use study, which included nine trucks for different engine manufacturers with model years newer than 2010 were included. A summary table of the vehicle engine information for the in-use tests and the related NOx emissions standards are shown in Table 2-9. There were four DDCs, three Volvos, one Navistar, and one Cummins engine truck tested in these studies.

Table 2-11 Test Trucks Information for CARB in-use Studies

Vehicle ID	Maker	Engine Size	Model Year	Horsepower	Vehicle Mileage	Standard/NTE/NTEThreshold		Studies
		SCR equipped				**g/bhp-h**		
2014/14 DDC #1	DDC		2014		135,000	Cert NOx:	0.09	ARB Misra et al., 2013, 2016
2014/14 DDC #2	DDC	12.8	2014	446	38,077			ARB Tu et al., 2016
2011/11 DDC_L	DDC	12.8	2011	410	23,000	Cert NOx:	0.13	ARB Misra et al., 2013, 2016
2011/11 DDC_H	DDC	12.8	2011	410	138,000	Cert NOx:	0.13	ARB Misra et al., 2013, 2016
2014/14 Volvo	Volvo		2014		62,000	Cert NOx:	0.06	ARB Misra et al., 2013, 2016
2013/13 Volvo	Volvo	12.4	2013	411	75,990			ARB Tu et al., 2016
2010/10 Volvo	Volvo	12.8	2010	405	68,000	Cert NOx:	0.11	ARB Misra et al., 2013, 2016
2010/10 Cum	Cummins	14.9	2010	450	13,500	Cert NOx:	0.25	ARB Misra et al., 2013, 2016
2013/13 Nav	Navistar	12.8 L	2013	446	105,171	NO_x STD: 0.20	NO_x NTE: 0.30	ARB Tu et al., 2016

NOx emissions for each route for each truck are shown in Figure 2-53, with the results shown on a g/bhp-hr basis. The 2013 Navistar generally showed higher in-use NOx emissions than the 2014 DDC #1 and the 2013 Volvo. The 2013 Navistar had a NOx emission factor of 0.365 g/bhp-hr and the 2014 DDC #1 had a NOx emission factor of 0.169 g/bhp-hr for route 1. The in-use NOx emissions were between 0.272-0.404 g/bhp-hr for the 2013 Navistar and 0.167-0.169 g/bhp-hr for the 2014 DDC #1 over route 1. The 2013 Navistar had NOx emissions of 0.266 g/bhp-hr and the 2014 DDC #1 had NOx emissions of 0.155 g/bhp-hr for route 2. The in-use NOx emissions were between 0.217-0.319 g/bhp-hr for the 2013 Navistar and between 0.092-0.221 g/bhp-hr for the 2014 DDC #1 over route 2. The 2013 Navistar had NOx emissions of 0.282 g/bhp-hr and the 2013 Volvo had NOx emissions of 0.173 g/bhp-hr for route 3. The in-use NOx emissions for the 2013 Navistar were between 0.203-0.385 g/bhp-hr and for the 2013 Volvo were between 0.107-0.291 g/bhp-hr for route 3.

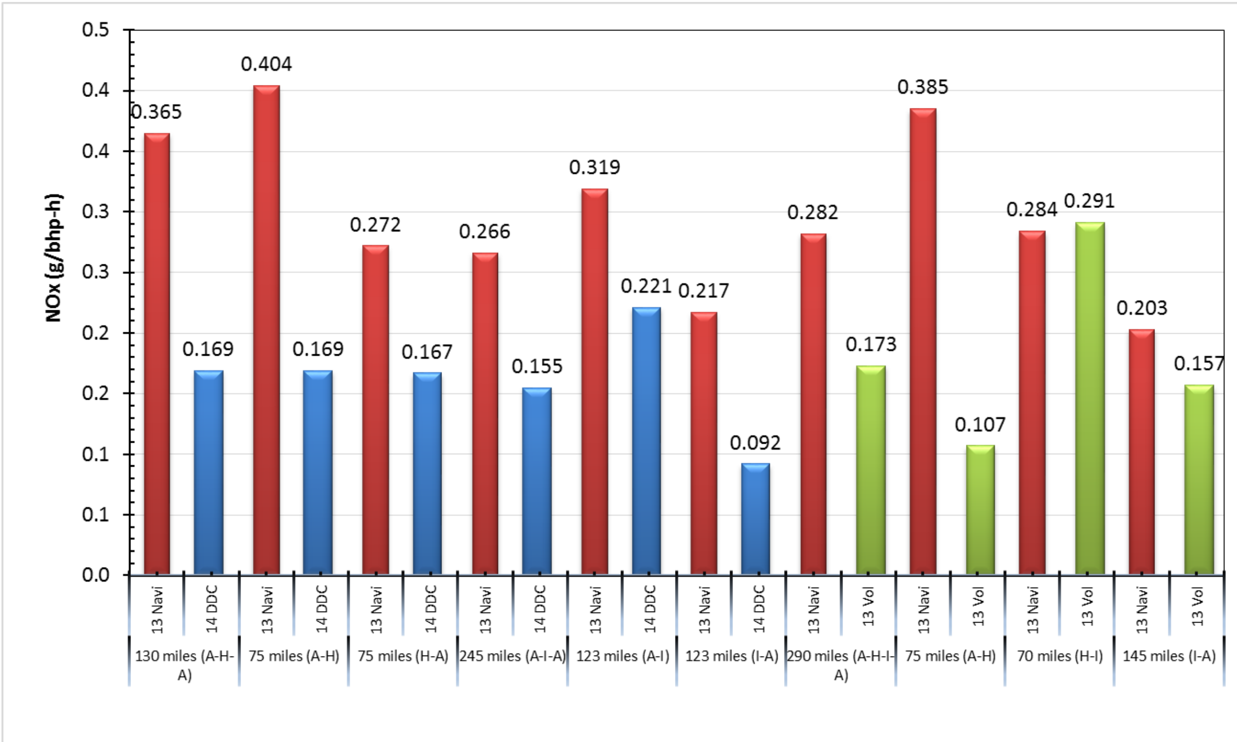


Figure 2-53 CARB El Monte In-use NOx study

Figure 2-54 shows the in-use testing results from Misra et al. (2013, 2016) Overall, the highway driving mode showed the lowest in-use NOx emissions, while the cold start period showed the highest in-use NOx emissions. The NOx emission factors of the arterial driving mode were a little higher than those of the highway driving, but much lower than those of the cold start period. NOx emissions during the highway driving were the only ones to meet the EPA 2010 standard, except for the 2014 DDC #1, while the NOx emissions of cold start were more than ten times higher than the standard. There weren't significant differences in the NOx emission factors between the different manufacturers over the same cycle, except for the 2014 Volvo for the cold start and both the 2014 Volvo and the 2010 Volvo for the arterial driving mode. For the load controlled and uncontrolled cycles, significant NOx emissions reductions were observed from the controlled compared to the uncontrolled driving.

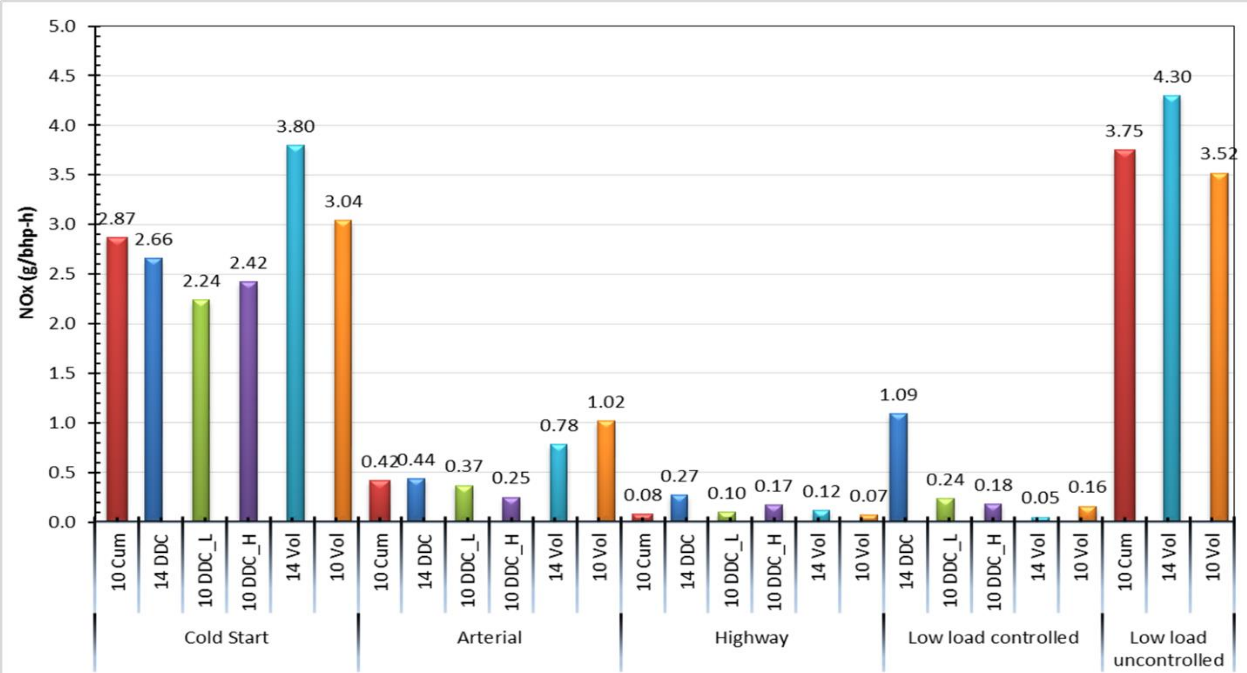


Figure 2-54 Misra et al. (2013, 2016) In-use NOx study

2.2.3 Summary Results for Different Engine Manufacturers

2.2.3.1 Volvo

Figure 2-55 shows the summary results of all the Volvo vehicles from the three chassis dynamometer and the two in-use emissions studies. There one 2012, two 2011 and one 2010 Volvo vehicles from the chassis dynamometer studies and a 2014, a 2013 and a 2010 Volvo vehicle from the in-use emissions studies. The NOx emission factors ranged from 0.234 g/bhp-hr to 1.81 g/bhp-hr for the chassis dynamometer tests and from 0.07 g/bhp-hr to 3.80 g/bhp-hr for the in-use emissions tests. For the chassis dynamometer tests, the emission factors of all the tested vehicles exceeded the EPA 2010 NOx standard, especially for the 2011 Volvo #1 over the Near Dock and the Local cycles. The 2012 Volvo had almost four times higher NOx emissions factor than those of the 2011 Volvo #1 for the hot UDDS cycle, even though the engine models of the 2012 Volvo and the 2011 Volvo #1 were similar in two studies. While the 2012 Volvo had a newer model year, lower mileage and lower maximum power, the NOx emissions were much higher than those for 2011 Volvo #1. The emission factors of the cold start UDDS of 2011 Volvo #1 were found to be higher than the factors for the hot UDDS. The Cruise 55 and the Cruise 65 showed similar and lower NOx emission values for both high speed driving cycles as the SCR catalysts were above their effective operating temperature. The highest NOx emissions were observed for the Near Dock and Local cycles, while the Regional cycle showed a relatively lower emission factor. The driving trace for the Regional cycle was more aggressive than other two driving cycles, which lead to the higher exhaust temperatures. For the Southern California CARB in-use studies, the emission factors of the 2013 Volvo met the 2010 standard, except for the Hesperia-CARB route. For the Northern California CARB in-use studies, the highest NOx emissions were found from the cold start phase and the lowest ones were from the highway phase. For the load controlled and uncontrolled cycles, significant NOx emissions reductions were observed for the controlled cycles. The emissions for the cold start, arterial, and uncontrolled low load driving were all above the NOx certification levels.

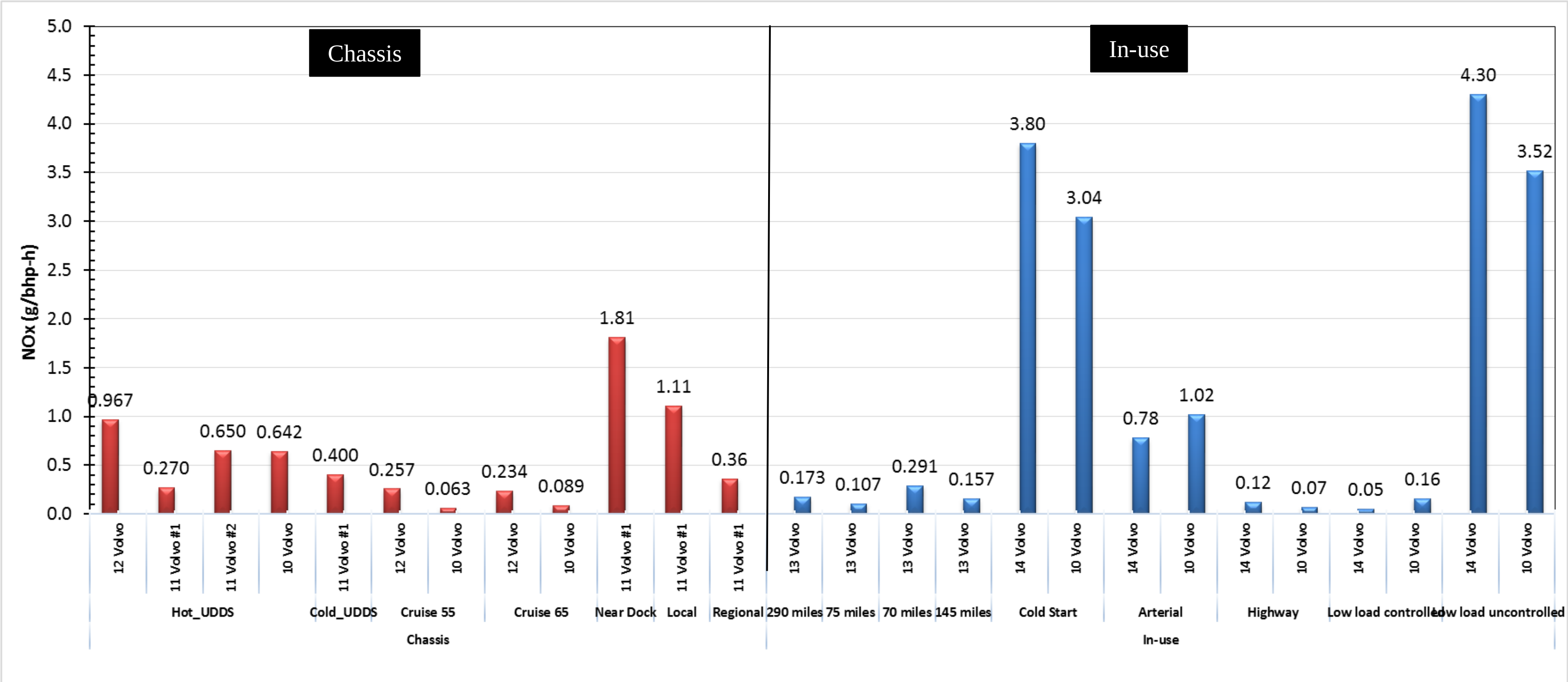


Figure 2-55 Summary Results for Volvo Trucks

2.2.3.2 Cummins

Figure 2-56 shows the summary results of all the Cummins vehicles from the two chassis dynamometer and the two in-use emissions studies. There were one 2015, one 2014 and two 2011 Cummins vehicles from the chassis dynamometer studies and a 2010 Cummins vehicle from the in-use emissions studies. The emission factor for the 2010 Cummins was converted from g/mi to g/bhp-hr by using the factor of 3.031. The NOx emission factors ranged from 0.023 g/bhp-hr to 0.90 g/bhp-hr for the chassis dynamometer tests and from 0.08 g/bhp-hr to 3.75 g/bhp-hr for the in-use emissions tests. For the chassis dynamometer tests, the NOx emission factors for the 2014 and 2015 Cummins vehicles ranged from 0.209 g/bhp-hr to 0.387 g/bhp-hr for the UDDS cycle, which were higher than the factors of 2011 Cummins vehicles, especially the NOx emission factor for 2011 Cummins #1. The NOx emission factors over the Cruise cycle for the 2014 and 2015 Cummins vehicles, ranging from 0.023 g/bhp-hr to 0.052 g/bhp-hr, were ten times lower than those of the UDDS cycles. For the three phases of the Port Cycles, the Near Dock cycle showed the highest NOx emissions, while the Regional cycle showed the lowest NOx emissions. The 2011 Cummins #1, with a lower mileage and higher maximum engine power, had lower NOx emission factors than the 2011 Cummins #3 for the UDDS and Port cycles, which suggested the NOx emission factors may have been impacted by the mileage of the vehicles. For the Northern California CARB in-use emissions tests, the highway driving mode of 2010 Cummins vehicle showed the lowest in-use NOx emissions, while the cold start period showed the highest in-use NOx emissions. The NOx emission factors of the arterial driving mode were a little higher than those of the highway driving, but much lower than those of the cold start period.

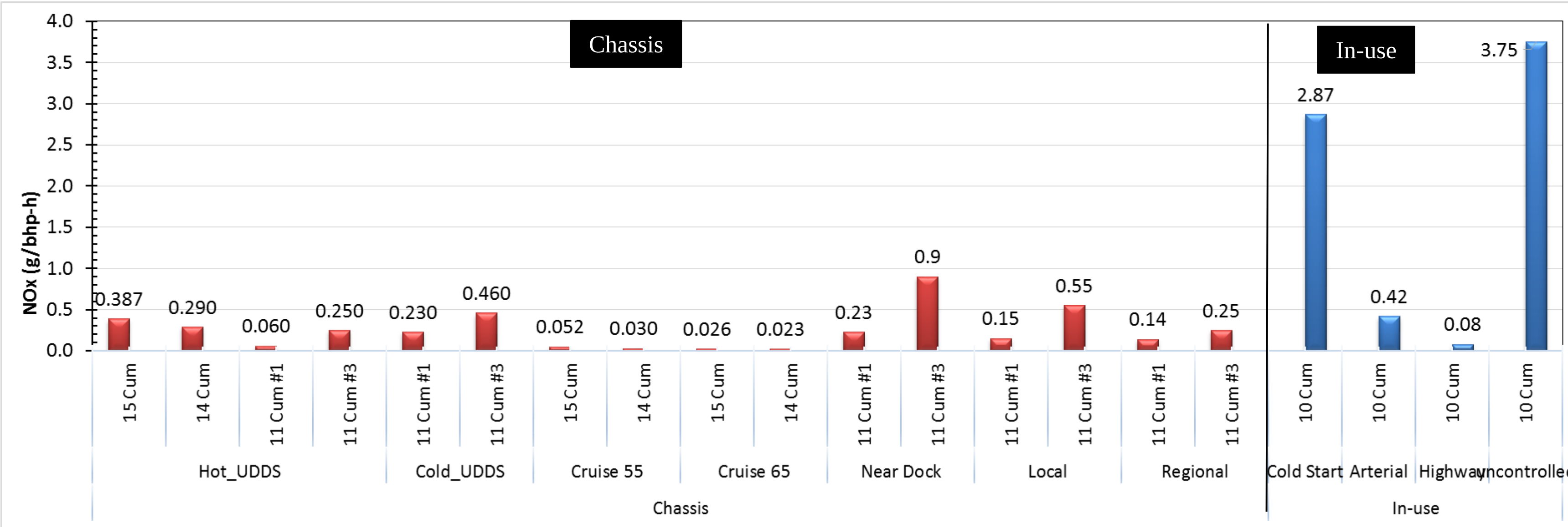


Figure 2-56 Summary Results Cummins Trucks

2.2.3.3 DDC

Figure 2-57 shows the summary results of all the DDC vehicles from the two chassis dynamometer and the two in-use emissions studies. There was only one 2014 DDC vehicle from the chassis dynamometer studies and two 2014 and one 2011 DDC vehicles from the in-use emissions studies. The NOx emission factors ranged from 0.069 g/bhp-hr to 0.137 g/bhp-hr for the chassis dynamometer tests and from 0.092 g/bhp-hr to 2.66 g/bhp-hr for the in-use emissions tests. For the chassis dynamometer tests, the Cruise cycles had much lower NOx emission factors, ranging from 0.069 g/bhp-hr to 0.078 g/bhp-hr, than those from the UDDS cycle, with the factor of 0.137 g/bhp-hr. For the Northern California CARB in-use emissions tests, the Misra et al. study showed that the highway driving modes had the lowest in-use NOx emissions, while the cold start emissions were the highest. The NOx emission factors of the arterial driving mode were a little higher than those of the highway driving, but much lower than those of the cold start period. The 2014 DDC #1 had a little higher NOx emissions than the 2011 DDC with either low mileage or high mileage over the same cycles. Even though more than 100,000 miles were added on the 2011 DDC, only minor increases in NOx emissions were found for the cold start and the highway trace when comparing factors between the 2011 DDC low mileage and the 2011 DDC high mileage tests, while arterial and low load uncontrolled driving modes showed lower NOx emissions.

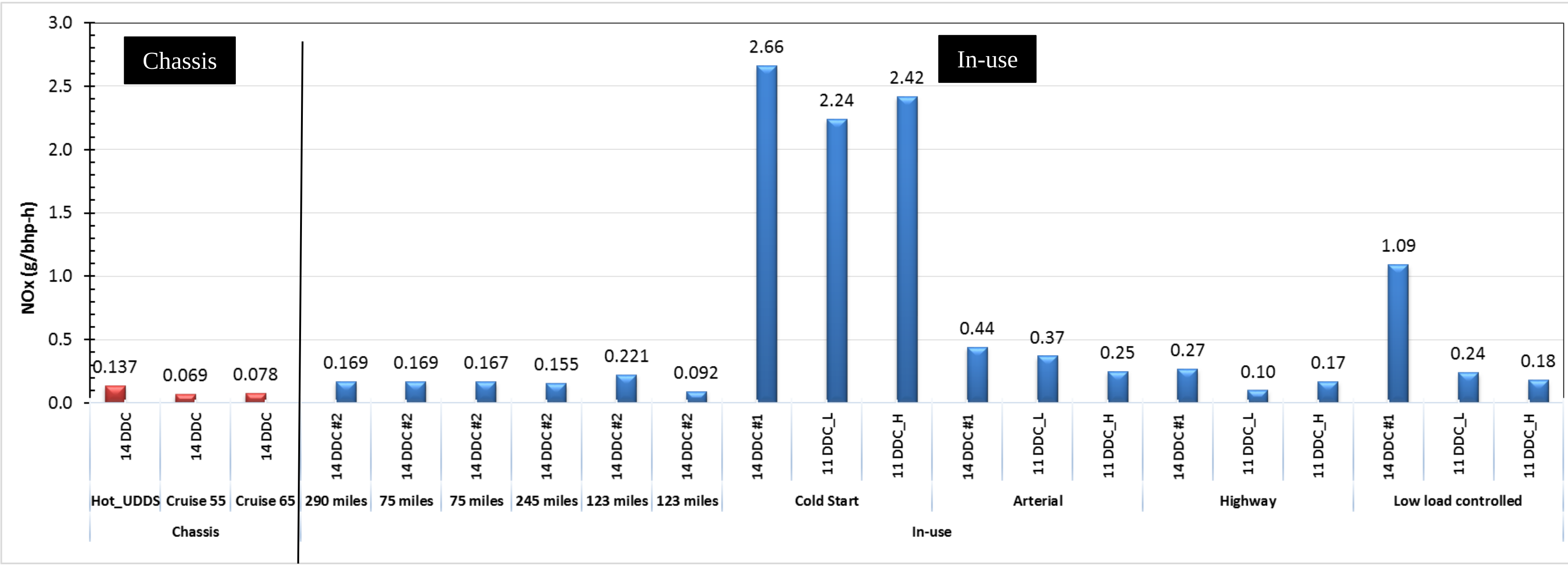


Figure 2-57 Summary Results for DDC Truck

3 Emissions Testing Procedures

The experimental procedures and methodologies for emissions and other testing are discussed in this section, including the test engines, test cycles, emissions measurements, and test procedures for running the chassis dynamometer testing, on-road testing, and engine dynamometer testing. The results of the emissions tests are presented in sections 4 and 5.

3.1 Test Engines

Two 2010-compliant HDDVs equipped with DPF and SCR systems that are certified to the 0.20 g/bhp-hr NOx standard were recruited for the testing, as shown in Table 3-1. The Manufacturer A equipped truck had an odometer of 135,000 miles and a 2014 engine model year. The Manufacturer B equipped truck had an odometer of 226,000 miles and a 2013 engine model year. The vehicles were selected based on availability, and having an engine size that would be suitable for the engine dynamometer testing.

Prior to procurement, each vehicle was inspected with a standard checklist to insure the vehicle was safe to drive and testable on a chassis dynamometer. The vehicles/engines were checked visually to identify possible signs of tampering, which would preclude the vehicle from being accepted into the program. The OBD system was also checked to make sure there are no active fault codes. The checklist that was utilized for this program is provided in Attachment A.

The vehicles were fueled with commercially available diesel fuel from a local distributor for all rounds of testing. For the engine testing, a blended fuel from several retail stations was procured to provide a more representative mixture. This fuel was also utilized for the initial chassis dynamometer testing on the Manufacturer A truck. Fuels for the other chassis dynamometer and on road testing was obtained from some of the same local fuel suppliers. Note that due to the tight specifications of CARB in-use diesel fuels, it is expected that the test fuel would produce equivalent or lower NOx emissions than a typical Federal certification diesel fuel.[4] As such, the test fuel blend should provide either equivalent or slight better emissions compared to a Federal certification diesel fuel. Fuel samples for the fuel used for the engine testing were analyzed by the CARB El Monte test laboratory for analysis, including the following properties: density (0.838 g/mL by ASTM D4052), sulfur (6.5 ppm by ASTM D5453), aromatics (19.8% by mass by ASTM D5186), polycyclic hydrocarbons (2.5% by mass by ASTM D5186), carbon weight fraction (86.4% by ASTM D5291), and cetane index derived from a density and distillation properties.

Table 3-1 specifications of the selected vehicles

Maker	Model Year	Engine size	Rated Power	Mileage	Afterteatment	NOx Standard
Manufacturer A	2014	12.8L	405 @1700 rpm	135,000	DOC/DPF/SCR	0.20 g/bhp-hr
Manufacturer B	2013	12.8L	500@1800 rpm	226,000	DOC/DPF/SCR	0.20 g/bhp-hr

[4] Hajbabaei, M., Johnson, K.C., Guthrie, J., and Durbin, T.D., 2013. Assessment of the Emissions from the Use of California Air Resources Board Qualified Diesel Fuels in Comparison with Federal Diesel Fuels. Int. J. of Engine Research, 14, 138-150.

3.2 Test Cycles, Test Matrix, and Test Methods

3.2.1 Chassis Dynamometer Testing

Each vehicle was tested over the four phases of the Heavy Heavy-Duty Diesel Truck (HHDDT) schedule developed by the California Air Resources Board (i.e., idle, transient, and cruise), with the exception of the creep cycle, the HHDDT short or (HHDDT-S) cycle, which is a high speed cruise schedule, and the UDDS. The characteristics of each test cycle are provided in Table 3-2, along with the preconditioning. Greater detail on the test cycles is provided in Attachment B. Three tests were conducted on each of the cycles listed in Table 3-2 for each of the test vehicles. Three cold start and three hot start tests were conducted over the UDDS cycle. The other tests were run in triplicate as hot running tests, where test iterations for each test cycle were conducted back to back such that the engine remains warm and preconditioned between each of the test iterations.

Table 3-2. Description of Chassis Dynamometer Test Cycles

Test Cycle	Time (s)	Avg. Speed (mph)	Distance (mi)	Preconditioning
UDDS	1,061	18.8	5.5	Cold/hot start
HHDDT Transient	668	14.9	2.9	15 minutes at 45 mph
HHDDT Cruise 55	2,083	39.9	23.1	15 minutes at 45 mph
HHDDT Cruise 65	760	49.9	10.5	15 minutes at 45 mph

Each test day began with a cold start UDDS test. After the completion of the cold start test at the beginning of the day, the vehicle was driven over a second UDDS cycle with no emissions collected such that the vehicle was sufficiently warmed up at the beginning of each test day to ensure that the vehicle was not in cold start mode prior to any of the hot start or running test sequences. The vehicle then went through a test sequence that includes each of the test cycles with the associated preconditioning cycle. An example of a typical sequence for each of the planned test days is provided in

Table 3-3. It should be noted that the actual test sequence would have varied from this sequence due to logistic considerations at the actual time of testing. The preconditioning was consistent between the different test sequences; however, irrespective of the actual order that the tests were conducted. For the hot start UDDS tests, the engine was soaked for 20 minutes between tests without having the engine on to mimic the soak time for the certification test procedure. For the other cycles that are being conducted as hot running tests, between each test sequence there was a soak period to allow for the analysis of the emissions from the just completed test, to replace the PM filters for the upcoming test, and to otherwise prepare the laboratory for the next test. This soak period is typically on the order of 10 to 20 minutes. Once these activities are completed, the vehicle went into the preconditioning for the next test, and then immediately following was run on the test sequence where emissions are collected. It should be noted that the test sequence includes a testing break/soak approximately midway through the test day. This period could be a regular 10 to 20 minute soak, or longer if for example a lunch break is taken. In the case of a break longer than 20 minutes for this or any of the other cold soak periods, the vehicle was warmed to a point where the oil or other relevant temperatures are raised to approximately the same level as for the more typical soak periods before beginning the 15 minutes at 45 mph. This should provide a more consistent level of preconditioning before each test sequence.

Table 3-3. Typical Test Sequence for Initial Chassis Dynamometer Testing

Day 1	
MEL/HDCD warm up	
Cold start UDDS + extra UDDS	Blue is full testing
Soak (engine off)	
UDDS	Yellow is soak
Soak (engine off)	
UDDS	Green Is break
Soak (engine off)	
UDDS	Red is prep/Conditioning
Testing break (Lunch)	
15 minutes @ 45 mph	Warm up/ Shutdown
Transient x 3	
Soak (engine off)	
15 minutes @ 45 mph	
Cruise x3	
MEL/HDCD shut down and Data process	

Day 2
MEL/HDCD warm up
Cold start UDDS + extra UDDS
Soak (engine off)
15 minutes @ 45 mph
Hi Speed Cruise x 3
MEL/HDCD shut down and Data process

Day 3
MEL/HDCD warm up
Cold start UDDS
MEL/HDCD shut down and Data process

Emissions tests were conducted on UCR's state-of-art heavy-duty chassis dynamometer. This facility is described in greater detail in Attachment C. The dynamometer handles a range of HDDVs, including buses, trucks and other vehicles. The dynamometer includes a 48" Electric AC Chassis Dynamometer with dual, direct connected, 300 horsepower motors attached to each roll set. The dynamometer applies appropriate loads to a vehicle to simulate factors such as the friction of the roadway and wind resistance, as would be experienced under typical in-use driving conditions. A driver accelerates and decelerates following a driving trace while on the dynamometer.

The road load coefficients were calculated based on the frontal area of the vehicle and a factor accounting for its general shape. A description of the road load calculations used is provided in Attachment D. The road load and associated coast down coefficients were verified with chassis dynamometer coast downs prior to testing. The vehicles were tested at a weight of 65,000 lbs. This weight was selected because the Federal Highway Administration estimates that a typical 5-axle semi-truck is loaded to approximately 65,000 lbs. GCW.[5,6] This is also the approximate weight of the combined weight of the MEL when it is being hauled by a class 8 tractor.

Emissions measurements for the initial round of chassis dynamometer testing were conducted using both the CE-CERT Mobile Emissions Laboratory (MEL) and a PEMS system, as described below under section 3.3.

3.2.2 On-Road Testing

The on-road tests were conducted over driving traces representative of or mimicking the UDDS, and the CARB-cruise cycles, as well as portions of a test route that has been used by CARB in in-use testing studies. To provide a comparison with in-use testing studies that have been conducted by CARB, UCR utilized a route that goes from the CE-CERT facility to Hesperia, from Hesperia to Indio, and then from Indio returning to the CE-CERT facility. This route is shown in Figure 3-1. This route incorporates a portion of driving on the 10 freeway near Indio that UCR has previously used to represent CARB Cruise cycle, and as such covered the Cruise cycle portion of the on-road testing. It should be noted that due to operational issues with the PEMS, the different routes were not necessarily conducted as a continuous sequence over the course of a single day. As such, the data were analyzed separately for each test segment, as discussed in sections 4 and 5.

UCR has previously conducted similar on-road measurements with standardized cycles as part of a research project on the European PMP method with CARB.[7,8] Previously, UCR has conducted such testing on a section of road near Thermal, California in the Palm Springs area. This section of road is shown in Figure 3-2. This section of road is located at an elevation near sea level and has an approximately 2 mile stretch of road without a stop sign, and where traffic is light and sparse minimizing the potential need for stopping. Although the road provides significant advantages, the length of the road was still too short for the duration of an entire UDDS test cycle. As such, sampling was split into three separate testing sections that were integrated to get the total mass emission rates. For the Manufacturer A truck, the 1st and 3rd segments of UDDS were conducted on Avenue 60, while the 2nd segment of UDDS was conducted on Avenue 62. For the Manufacturer B truck, the 1st and 3rd segments of UDDS were conducted on Avenue 62, while the 2nd segment of UDDS was conducted on Avenue 60. A special segmented UDDS cycle driving trace was programmed into a drivers aid computer that the driver followed over the course of the cycle, keeping in mind that we did not take undue safety risks while conducting the testing.

[5] Patrick Couch and Jon Leonard, 2011, Characterization of Drayage Truck Duty Cycles at the Port of Long Beach and Port of Los Angeles, Final Report prepared by TIAX for the Ports of Long Beach and Los Angeles, March.

[6] Table III-4, Comprehensive Truck Size and Weight Study, 2000. Federal Highway Administration.

[7] Durbin, T.D., Jung, H., Cocker, D.R., Johnson, K., and Chaudhary, A. 2008. Evaluation of the Proposed New European Methodology for Determination of Particle Number Emissions and Its Potential for In-Use Screening. California Air Resources Board, August.

[8] Johnson, K.C., Durbin, T.D., Jung, H., Chaudhary, A., Cocker III, D.R., Herner, J.D., Robertson, W.H., Huai, T., Ayala, A., and Kittelson, D. 2009. Evaluation of the European PMP Methodologies during On-Road and Chassis Dynamometer Testing for DPF Equipped Heavy Duty Diesel Vehicles. Aerosol Science and Technology, Vol. 43, pp. 962-969.

Figure 3-1. In-use Testing Route from UCR to Hesperia to Indio Returning to UCR

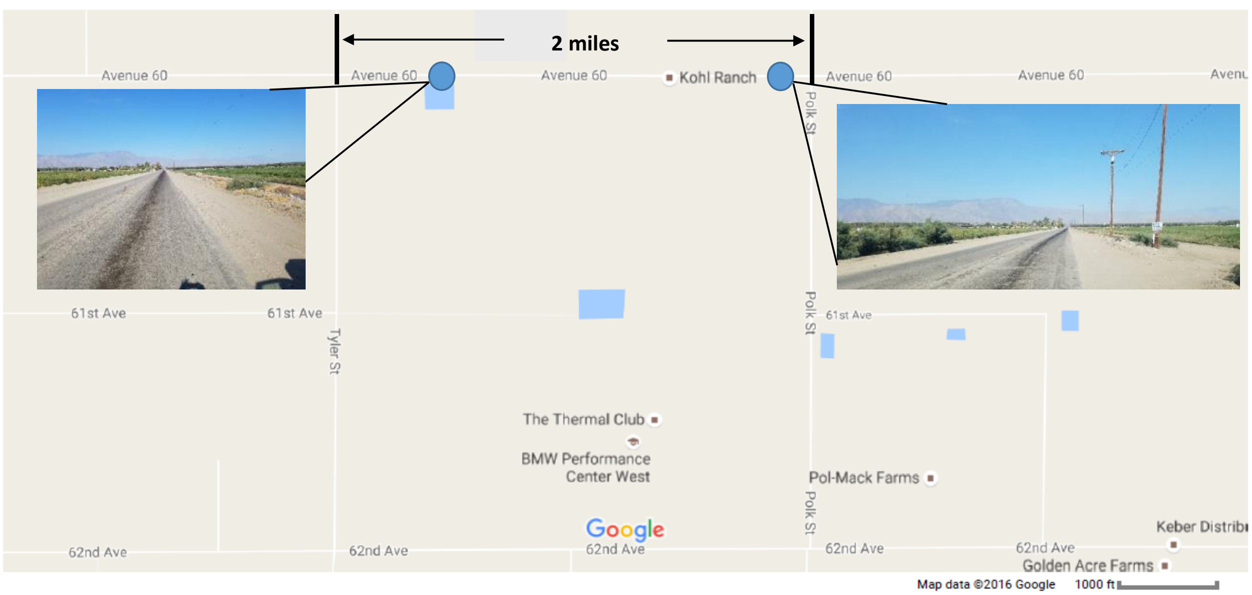


Figure 3-2. In-use Testing Route at Thermal for the UDDS

A description of an example daily on-road test sequence is provided in Table 3-4. This sequence was conducted three times with each vehicle, such that testing for each route or in-use test cycle was conducted in triplicate, including the trip to Hesperia, from Hesperia to Indio/Thermal, an in-use UDSS in Thermal, and a return trip from Indio/Thermal. It should be noted that the actual sequence varied due to logistical considerations, as discussed above.

Table 3-4. Typical Daily Test Sequence for On-Road Testing

Days 1, 2, and 3	
MEL/HDCD warm up	
Riverside to Hesperia	Blue is full testing
Soak (engine off)	
Hesperia to Indio	Yellow is soak
Testing break (Lunch)	
UDDS	Green Is break
Soak (engine off)	
UDDS	Red is prep/Conditioning
Soak (engine off)	
Indio to Riverside	Warm up/ Shutdown
MEL/HDCD shut down and Data process	

Emissions measurements for the on-road testing was conducted using the PEMS system, as described below under section 3.3. The CE-CERT MEL was utilized as a load for on-road testing, but was not utilized for emissions measurements.

3.2.3 Engine Dynamometer Testing

As part of this program UCR worked with a local repair shop to uninstall the engines from the trucks for installation on the engine dynamometer. In addition to the engine itself, this included some ancillary equipment that was needed to allow the engine to be operated on the engine dynamometer. This process included both the mechanical and relevant electrical connections in terms of getting the engine operating.

The test cycles included two standard engine-dynamometer cycles (the FTP and the ramped modal cycle - supplemental emissions test, RMC-SET) that was developed based on the CFR specifications. The engine dynamometer versions of the CARB 4-mode cycles were also used, including the CARB-transient, CARB-cruise, and CARB-high-speed cruise. These cycles were taken from the generalized versions derived for use in the ACES study.[9] The characteristics of each test cycle are provided in Table 3-5, with greater detail on the test cycles is provided in Attachment E. An engine dynamometer version of the UDDS was also developed. This UDDS cycle was developed by translating relevant engine operational data from the chassis dynamometer testing, including the engine torque, rpm, and power for each specific engine. A separate UDDS cycle was constructed for each of the test vehicles/engines, while the generalized versions derived for use in the ACES study. Preliminary tests with each test cycle were conducted with each engine to insure the proper operation of the engine over the cycle prior to beginning the testing. This also included setting the idle point and running engine maps to map out the operational conditions.

[9] Clark, N.N., M. Gautam, M., W.S. Wayne, D. Lyons, W. F. Zhen, C. Bedick, R.J. Atkinson, and D.L. McKain. 2007a. Creation of the "Heavy Heavy-Duty Diesel Engine Test Schedule" for representative Measurement of Heavy-Duty Engine Emissions, CRC Report No. ACES-1, CRC Website at crcao.org, July.

Table 3-5. Description of Engine Dynamometer Test Cycles

Test Cycle	Time (s)	Test Type
FTP	1,200	Cold/hot start
Ramped Modal Cycle	2,380	Hot running
UDDS	1,061	Hot start
HHDDT Transient	668	Hot running
HHDDT Cruise 55	2,083	Hot running
HHDDT-S Cruise 65	760	Hot running

In terms of preconditioning, the FTPs were conducted both as hot starts and cold starts in triplicate. The FTPs were conducted in the morning as a cold start FTP followed by a 20 minute soak and then a hot start FTP, consistent with the certification procedure. The UDDS tests were also conducted as hot start tests, with a 20 minute soak in between them, in order to provide results that can be more directly compared to the chassis dynamometer test results. The other tests were conducted as hot running tests. Each of the separate hot running tests were preconditioned by one iteration of that test as a warm up, consistent with the certification procedures for hot running tests (40 CFR Part 1065.518). Table 3-6 provides an example the test matrix for the engine testing. It should be noted that the actual test sequence varied from this sequence due to logistic considerations at the actual time of testing. The preconditioning remained consistent between the different test sequences; however, irrespective of the actual order that the tests were conducted.

Table 3-6. Test Sequence for Engine Dynamometer Testing

Day 1	
MEL/HDCD warm up	
Cold start FTP	Blue is full testing
Soak (engine off)	
FTP	Yellow is soak
Soak (engine off)	
Ramped Modal Cycle Warmup	Green Is break
Ramped Modal Cycle	
Soak (engine off)	Red is prep/Conditioning
Transient warm up	
Transient x 3	Warm up/ Shutdown
Testing break (Lunch)	
UDDS warm up	
Soak (engine off)	
UDDS	
Soak (engine off)	
UDDS	
Soak (engine off)	
UDDS	
MEL/HDCD shut down and Data process	

Day 2
MEL/HDCD warm up
Cold start FTP
Soak (engine off)
FTP
Soak (engine off)
Ramped Modal Cycle Warmup
Ramped Modal Cycle
Soak (engine off)
Hi Speed Cruise warm up
Hi Speed Cruise x 3
Testing break (Lunch)
Cruise warm up
Cruise x3
MEL/HDCD shut down and Data process

Day 3
MEL/HDCD warm up
Cold start FTP
Soak
FTP
Soak
Ramped Modal Cycle Warmup
Ramped Modal Cycle
MEL/HDCD shut down and Data process

The engine tests were performed in UCR's heavy-duty engine dynamometer test facility. The test cell is equipped with a 600 horsepower (hp) GE DC electric engine dynamometer that was obtained from the EPA's National Vehicle and Fuels Emission Laboratory in Ann Arbor, MI. This unit is designed for quick response and stable control under both steady state and transient conditions for horsepowers up to 600 hp with a 1575 ft-lb torque limit. The combustion air system provides air to the engine at a controlled temperature setpoint from 20°C to 30°C with an accuracy of ±2°C from setpoint. The system also provides humidity control for the combustion air and controls dew point from a setpoint of 42°F to 60°F. This unit also meets the SAE J-1973 standard for supplying conditioned air to turbocharged engines equipped with charge air-cooling.

An important element of the engine dynamometer testing was the set up the engine on the dynamometer. CE-CERT worked with both engine manufacturers in setting up their respective engines. This included developing electronic signals to simulate the signals that would be received by the engine when it is operated in the truck itself, and clearing any diagnostic codes found that might suggest issues with the engine operation. For the manufacturer A engine, this included clearing faults related to two urea tank heated circuits (using 25 watt resistors), and an idle validation logic code. For the manufacturer A engine, several codes that we were unable to clear prior to the engine testing related to dash communication, as summarized below. It was initially thought that such codes would not impact the operation of the engine on the dynamometer. After analyzing the testing results, however, the engine manufacturer indicated that the lack of dash communication caused the engine to run in "cold start" mode, which retarded the fuel injection timing, causing the engine to run in a lower NOx emitting mode. This is discussed in greater detail in section 4.1.2.3.

11 RDCM-ReductantCtrl

MIL on

2 fault code entries

U0155Lost Communication With Instrument Panel Cluster (IPC) Control Module

U0141 Lost Communication With Body Control Module "A"

10 ECM-EngineControl

MIL on

2 fault code entries

U0001 High Speed CAN Communication Bus

U0141 Lost Communication With Body Control Module "A"

Emissions measurements for the engine dynamometer testing was conducted using both the CE-CERT MEL and a PEMS system, as described below under section 3.3. The concurrent testing with the MEL and a PEMS allowed for comparisons and correlations with the on-road testing and chassis dynamometer testing.

3.2.4 Final Chassis Dynamometer Retesting

Under this task, the two test vehicles were retested on the chassis dynamometer following the reinstallation of the engine. The vehicles was tested over the same five driving cycles described in section 3d, namely the UDDS, CARB-creep, CARB-transient, CARB-cruise, and CARB-high-speed cruise. Testing was conducted in triplicate over each of the cycles. The tests were run either as hot start tests (for the UDDS) or hot running tests (for the CARB-transient, CARB-cruise, and CARB-high-speed cruise) to provide consistency with the initial chassis dynamometer testing. Additionally, a single cold start UDDS was conducted at the start of the test day following by an additional UDDS with no emissions collected to ensure full warmup of the vehicle. A description of an example test sequence for each vehicle is provided in Table 3-7. It should be noted that the actual test sequence varied from this sequence due to logistic considerations at the actual time of testing. The preconditioning remained consistent between the different test sequences; however, irrespective of the actual order that the tests were conducted.

Emissions measurements for the final chassis dynamometer tests were conducted using only the CE-CERT MEL, as described below under section 3.3. PEMS measurements was not made for this part of the testing.

Table 3-7 Test Sequence for Test Day for Final Chassis Dynamometer Testing

Day 1	
MEL/HDCD warm up	
Cold start UDDS + extra UDDS	Blue is full testing
Soak (engine off)	
UDDS	Yellow is soak
Soak (engine off)	
UDDS	Green Is break
Soak (engine off)	
UDDS	Red is prep/Conditioning
Testing break (Lunch)	
15 minutes @ 45 mph	Warm up/ Shutdown
Transient x 3	
Soak (engine off)	
15 minutes @ 45 mph	
Hi Speed Cruise x 3	
Soak (engine off)	
15 minutes @ 45 mph	
Cruise x3	
MEL/HDCD shut down and Data process	

3.3 Emissions and Engine Parameter Measurements

The primary emissions measurements were collected with UCR's Center for Environmental College of Engineering Research and Technology's (CE-CERT's) Mobile Emissions Laboratory

(MEL) for the chassis and engine dynamometer testing. The MEL measures criteria pollutants, particulate matter (PM), and toxics with a CVS system meeting 40 CFR Part 1065 requirements (Cocker et al., 2004a,b).[10,11] The MEL is described in greater detail in Attachment C. As discussed in the previous section, MEL was located next to the UCR heavy-duty chassis or engine dynamometer to measure emissions. The MEL was the second HDD lab in the United States to meet 40 CFR Part 1065 specifications and has successfully carried out cross laboratory comparisons for both gaseous and PM emissions with Southwest Research Institute in 2007 and 2009.[12,13] Earlier cross correlation measurements were carried out with NREL in Denver in 2005, as well as with the CARB lab in Los Angeles. Results from UCR's mobile lab are recognized by the engine manufacturers and regulatory groups, including the US EPA and CARB, and the data are often used to support regulation. For all tests, standard emissions measurements of total hydrocarbons (THC), nonmethane hydrocarbons (NMHC), methane (CH_4), carbon monoxide (CO), oxides of nitrogen (NO_x, NO, NO_2), CO_2, and PM, were measured. The quality control/quality assurance procedures for the MEL are provided in Attachment F.

In addition to the primary emissions measurements, additional emissions measurements was also made with a PEMS system for gaseous and PM emissions. The PEMS measurements are included to provide an independent confirmation of emission differences between chassis and engine dynamometer testing and to gather information on the comparability of PEMs to CVS testing. CE-CERT is equipped with a fully 1065 approved gaseous and PM PEMS system for on-road and off-road applications. The main system utilized was the AVL M.O.V.E. system for gaseous emission measurements and the AVL 494 system for PM measurements. The AVL M.O.V.E. is equipped with a non-dispersive ultraviolet (NDUV) analyzer for measuring oxides of nitrogen (NO and NO_2), a non-dispersive infrared (NDIR) analyzer for measuring CO and CO_2, and a flame ionization detector (FID) for measuring THC. A Semtech ECOSTAR was also used for the engine dynamometer testing for the Manufacturer B truck. The gaseous data is measured as a concentration and is time aligned and flow weighted to the exhaust flow for total mass reporting. All time alignment and flow weighting is performed as part of the post processor systems for both PEMS. The exhaust flow meter is integrated with the gaseous PEMS and is designed to work over a wide range of exhaust flows for transient vehicle testing. The exhaust flow meter uses differential pressure as its measurement principle.

The PM PEMS measurement system was the AVL 494 PM system, which was released in mid-2010. It combines AVL's 483 micro soot sensor (MSS) with their gravimetric filter module (GFM) option. The AVL 483 MSS measures the modulated laser light absorbed by particles from an acoustical microphone. The measurement principle is directly related to elemental carbon (EC) mass (also called soot), and is robust and found to have good agreement with the reference

[10] Cocker III, D. R., Shah, S., Johnson, K., Miller, J. W., Norbeck, J., 2004a, *Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. I Regulated Gaseous Emissions*, Environ. Sci. & Technology, 38,2182-2189.

[11] Cocker, D.R.; Shah, S.D.; Johnson, K.J.; Zhu, X; Miller, J.W.; Norbeck, J.M., 2004b, *Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 2. Sampling for Toxics and Particulate Matter,* Environ. Sci. & Technology, 38, 6809-6816.

[12] Miller, J.W., T.D. Durbin, K. Johnson, D.R. Cocker. 2008. Measurement Allowance Project – On-Road Validation. California Air Resources Board, January.

[13] Johnson, K., Durbin, T.D., Jung, H., Cocker, D.R., Yusuf Khan, M. 2010. Validation Testing for the PM-PEMS Measurement Allowance Program. Final Report by UC Riverside to the California Air Resources Board under Contract No. 07-620, November.

gravimetric method for EC dominated PM. The GFM is then utilized in conjunction with a post processor that utilizes the filter and a soluble organic fraction (SOF) and a Sulfate model to estimate total PM from the soot and gravimetric filter measurements. One gravimetric filter can be sampled per day or test and the continuous PM concentration is recorded at 1 Hz with an option of 10 Hz data. The combined MSS+GFM system has received type approval by EPA as a total PM measurement solution for in-use testing, thus making it one of the few 1065 compliant PM PEMS systems.

In addition to the emissions related species, UCR also measured engine broadcast messages from the engine control module (ECM) and temperatures related to the aftertreatment system. The ECM data included, where available, percent load, torque, rpm, coolant, intake and exhaust temperatures, and other pertinent engine condition related information. The scope of the J1939 parameters collected was similar to that being collected in an activity data logging studies being conducted by UCR (Boriboonsomsin et al., 2017; Durbin et al., 2018), and included 169 J1939 channels. A listing of these channels is provided in Attachment G. UCR also obtained information on the temperatures for the aftertreatment systems through the ECU.

4 Emissions Results

The emissions test results are presented in this section. The figures for each pollutant show the results for each vehicle/laboratory/cycle combination based on the average of tests conducted on that particular test combination. Emissions were measured with both MEL and PEMS systems for most pollutants and most testing combinations, with the exception of the n-road testing and the final chassis dynamometer testing. The error bars on the figures are the standard deviation over all tests for each test combination. The results for all emissions tests on the two test vehicles are provided in Appendix H.

4.1 NO_x Emissions

4.1.1 NO_x Emission rates

4.1.1.1 NOx Emission rates

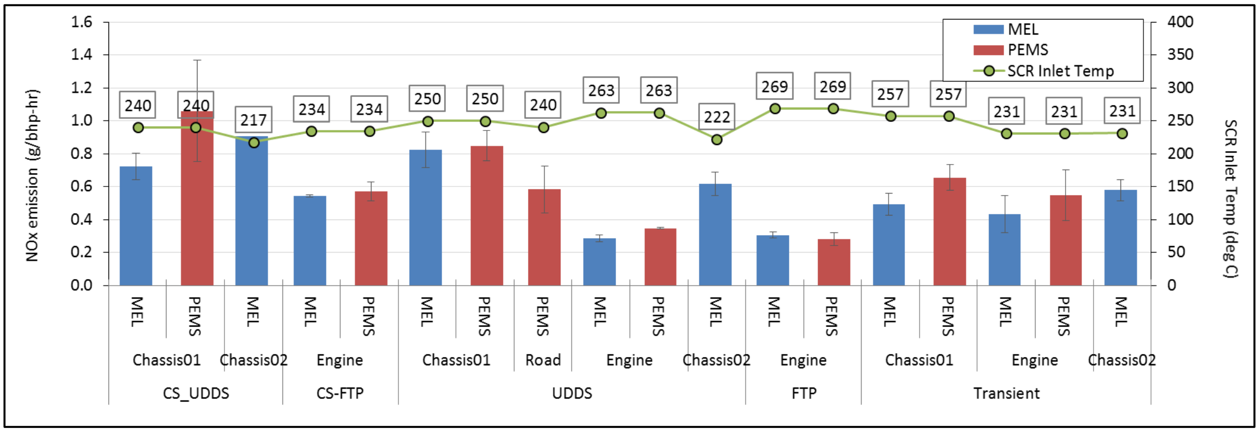
NOx emissions for the Manufacturer A and Manufacturer B trucks are shown on a g/bhp-hr and a g/mi basis, respectively, in Figure 4-1 and Figure 4-2 for the urban driving cycles, including the CS-UDDS, UDDS, CS-FTP, FTP and HHDDT-transient cycles. These Figures include the results for the initial and final Chassis dynamometer tests, the on-road tests, and the engine dynamometer tests. The average SCR inlet temperature for each cycle is also included in these figures. The results for the Manufacturer A and Manufacturer B trucks are shown in the top and bottom panels, respectively, of each figure. It should be noted that discussions with Manufacturer A suggested that the engine could have been operating in a cold start mode during the engine dynamometer testing due in part to an absence of vehicle dashboard cluster communication, which potentially caused the engine to operate with retarded fuel injection timing. This explanation needs to be further evaluated; however, with a deeper investigation of the emission control related ECU parameters along with engine laboratory test conditions.

The Manufacturer A truck showed a range in emissions from about 0.3 to 1.1 g/bhp-hr over all of the urban test conditions and both the MEL and PEMS. The NOx emissions for the weighted FTP (1/7×Cold_FTP +6/7×Hot_FTP) cycle were 0.34 for the Manufacturer A truck, which is above the 0.2 g/bhp-hr certification standard and the 0.06 g/bhp-hr certification value. The CS-UDDS and regular UDDS on the chassis dynamometer showed the highest ,emissions for a specific cycle, with emissions ranging from 0.7 to 0.8 g/bhp-hr, based on the MEL measurements. The lowest emissions were found for the engine dynamometer UDDS and FTP cycles, with emissions of approximately 0.3 g/bhp-hr for the MEL The transient, CS-FTP and on-road UDDS results were in the middle of the other results, ranging from about 0.44 to 0.9 g/bhp-hr. In comparing the initial and final chassis dynamometer testing for the UDDS and Transient cycles, there were some differences between the different tests, but there was not a consistent trend of higher or lower emissions for either the initial or final tests, or between the g/bhp-hr and g/mi results.

The Manufacturer B truck showed a similar range, with emissions ranging from 0.16 g/bhp-hr to 1.1 g/bhp-hr for all test conditions and instruments. The NOx emissions for the weighted FTP (1/7×Cold_FTP +6/7×Hot_FTP) cycle were 0.45 g/bhp-hr for the Manufacturer B truck, which is above the 0.2 g/bhp-hr certification standard and the 0.17 g/bhp-hr certification value. The CS-UDDS and CS-FTP cycles showed the highest emissions, ranging from 0.6 to 1.1 based on the MEL measurements. The UUDS of chassis dynamometer results were 0.4 g/bhp-hr while the on-road and engine dynamometer UDDS cycles were on the order of 0.2 g/bhp-hr. Interestingly, the transient results showed the biggest differences between the chassis dynamometer and engine dynamometer testing, with the chassis dynamometer tests being below 0.2 g/bhp-hr compared to 0.7 g/bhp-hr for the engine dynamometer test. In comparing the initial and final chassis dynamometer test results, the results were similar for the UDDS cycle, but were higher for the final test for the Transient test.

In comparing the results for the different test cycles between the different testing conditions (i.e., chassis dynamometer, on-road, and engine dynamometer), the results showed mixed trends, depending on the vehicle and test cycle. The Manufacturer A truck for the UDDS showed the highest emissions for the chassis dynamometer testing, followed by the on-road testing, with the lowest UDDS emissions for the engine dynamometer testing. As discussed in section 3.2.3, discussions with Manufacturer A suggested that the engine could have been operating in a cold start mode during the engine dynamometer testing due in part to an absence of vehicle dashboard cluster communication, which potentially caused the engine to operate with retarded fuel injection timing, as discussed below in section 4.1.2.3. This explanation needs to be further evaluated; however, with a deeper investigation of the emission control related ECU parameters along with engine laboratory test conditions. Interestingly, the transient test for the Manufacturer A truck were comparable between the chassis dynamometer and engine dynamometer tests, despite the cold start mode operation on the engine dynamometer. The Manufacturer B truck also showed the highest UDDS results for the chassis dynamometer testing, with comparable results for the on-road and engine dynamometer UDDS results. The Manufacturer B truck showed opposite results for the transient cycle, however, with lower emissions for the chassis dynamometer testing compared to the engine dynamometer testing results.

On a g/mi basis, the emissions for the urban cycles ranged from 2.3 to 5.0 g/mi over the CS_UDDS, UDDS, and transient cycles for the Manufacturer A truck. The Manufacturer B truck showed lower emissions for the UDDS (1.0 to 1.6 g/mi) and transient (0.7 to 1.3 g/mi) cycles, while the CS_UDDS results were about 3 g/mi.



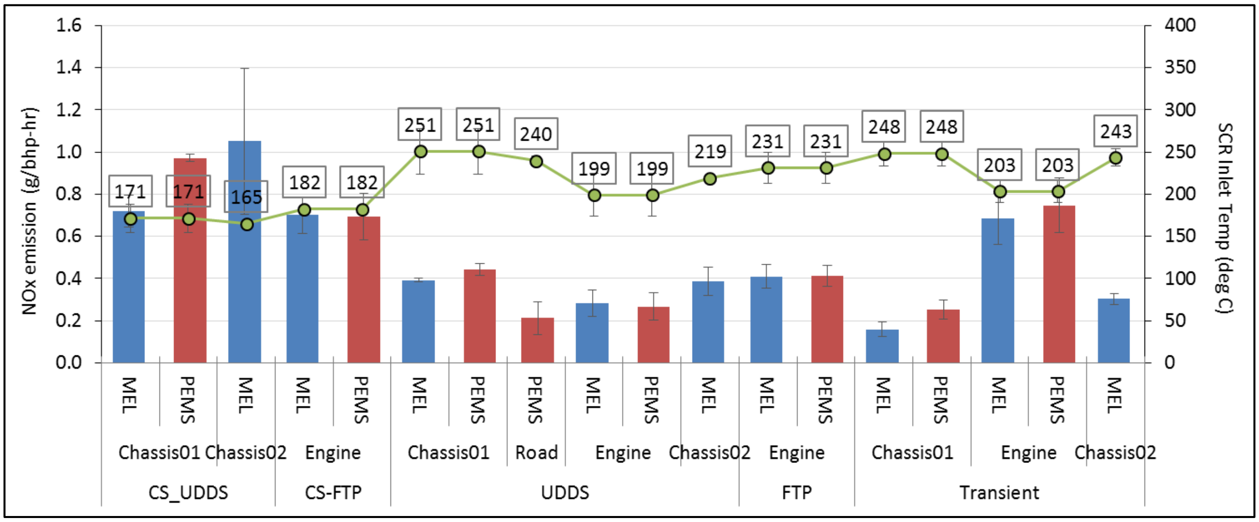
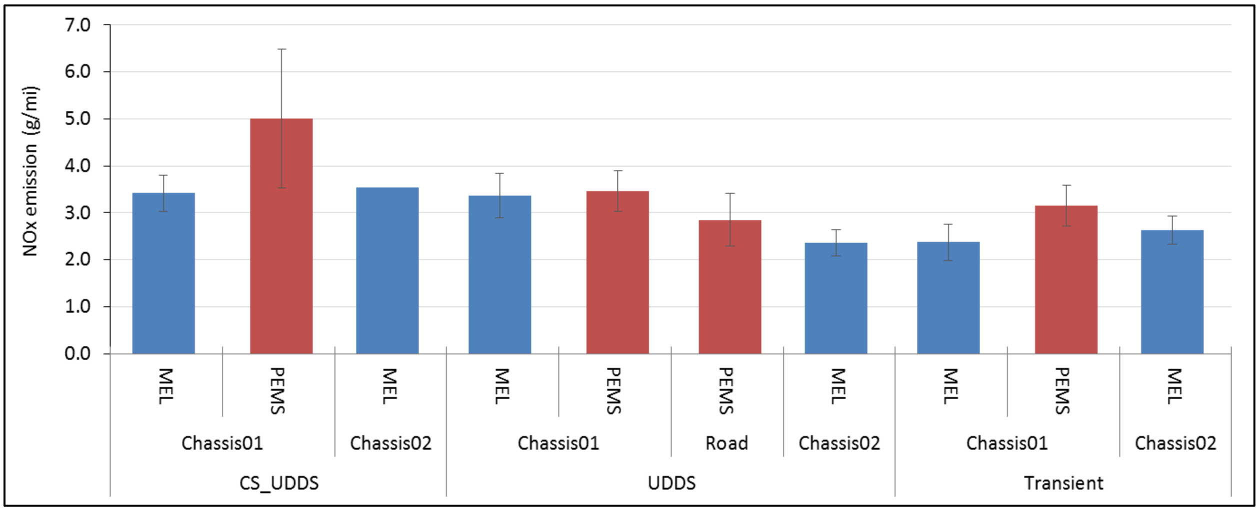


Figure 4-1 Average NOx Emissions on a g/bhp-hr Basis for the urban cycles for the Manufacturer A Truck (top) and Manufacturer B Truck (bottom)



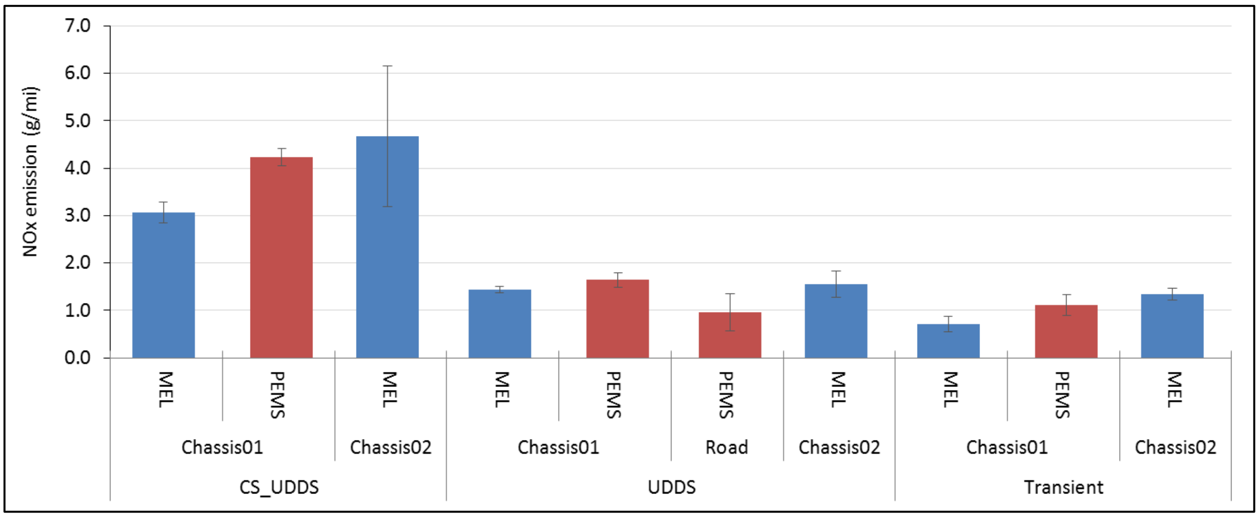


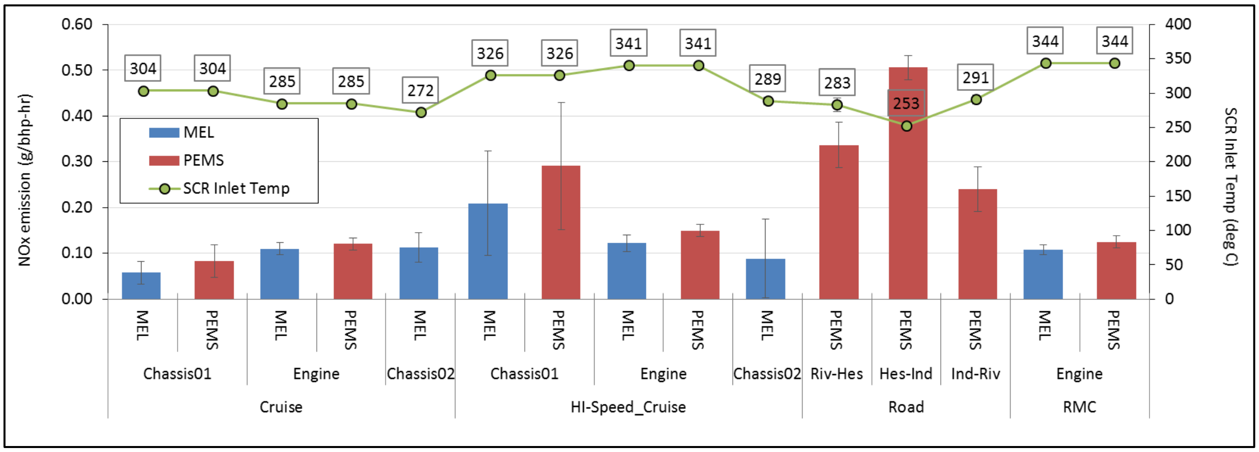
Figure 4-2 Average NOx Emissions on a g/mi Basis for the urban cycles for the Manufacturer A Truck (top) and Manufacturer B Truck (bottom)

NOx emissions for the Manufacturer A and Manufacturer B trucks are shown on a g/bhp-hr and a g/mi basis, respectively, in Figure 4-3 and Figure 4-4 for the highway driving cycles, including the cruise and high-speed cruise cycles, as well as the results from the on-road and RMC engine dynamometer testing. The average SCR inlet temperature for each cycle is also included in these figures.

The results for the freeway/RMC tests were generally lower than those for the urban cycles. For the Manufacturer A truck, the cruise results were on the order of 0.1 g/bhp-hr, while the high-speed cruise results were 0.3 g/bhp-hr or less. For the Manufacturer B truck, the cruise and high speed cruise results were on the order of 0.27 g/bhp-hr or less based on the MEL results. The on-road testing results were higher for the both trucks, ranging from 0.22 to 0.50 g/bhp-hr for Manufacturer A and from 0.35 to 0.49 g/bhp-hr for Manufacturer B for the Hesperia test route. Note that the Riverside to Hesperia test route is primarily uphill driving that puts a higher load on the engine, which could cause the higher emissions for that test route. While the Hesperia to Indio route includes considerable downhill driving, where the load on the engine is relatively low, which could be contributing to the higher emissions for that test route segment on a g/bhp-hr basis. Although there were some differences between the initial and final Cruise and Hi-Speed Cruise cycles, there were not any consistent differences between the initial and final testing.

In comparing the results for the different test cycles between the different testing conditions (i.e., chassis dynamometer, on-road, and engine dynamometer) for the freeway/steady state tests, the results were more consistent than those of urban cycles. The Manufacturer A truck for the cruise showed consistent emissions between different testing conditions, despite operating in a cold start mode for the engine dynamometer testing. The NOx emissions for the hi-speed cruise for the Manufacturer A truck were comparable between the engine dynamometer and the second chassis dynamometer tests, with higher emissions of the first chassis dynamometer testing. The Manufacturer B truck showed more consistent results between the different testing conditions for hi-speed cruise than the cruise cycle. The cruise for the Manufacturer B truck were comparable between the engine dynamometer and the second chassis dynamometer tests, with slightly higher emissions of the first chassis dynamometer testing. The on-road testing results were higher for the both trucks compared with the cruise and hi-speed cruise cycles in the chassis and engine dynamometer testing. Note that the Riverside to Hesperia route is an uphill route and the Hesperia to Indio route includes considerable downhill driving.

On a g/mi basis, NOx emissions averaged 0.2 g/mi for the cruise cycle and 0.7 g/mi for the Hi-speed cruise for the Manufacturer A truck. For the on-road freeway testing for the Manufacturer A truck, average NOx emissions were 1.7 g/mi for the Riverside-Hesperia route, 1.1 g/mi for the Hesperia-Indio route, and 0.92 g/mi for the Indio-Riverside route. The NOx emissions on a g/mi basis were higher for the Manufacturer B truck, at approximately 0.6 to 0.8 g/mi for the cruise and high speed chassis dynamometer cycles. For the on-road freeway testing for the Manufacturer B truck, average NOx emissions were 2.8 g/mi for the Riverside-Hesperia route, 0.9 g/mi for the Hesperia-Indio route, and 1.3 g/mi for the Indio-Riverside route. The Manufacturer B truck had much higher NOx emissions for the Riverside-Hesperia route than the values of the other two routes. The Riverside-Hesperia route is an uphill route, where the load on the engine is relatively higher for a given speed, which could be contributing to the higher emissions for that test route segment on a g/mi basis.



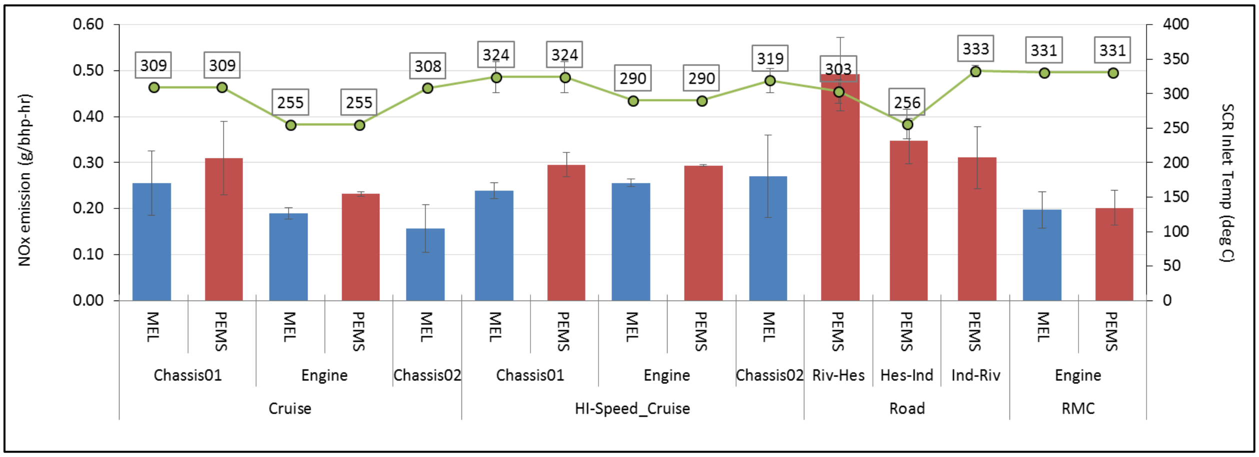
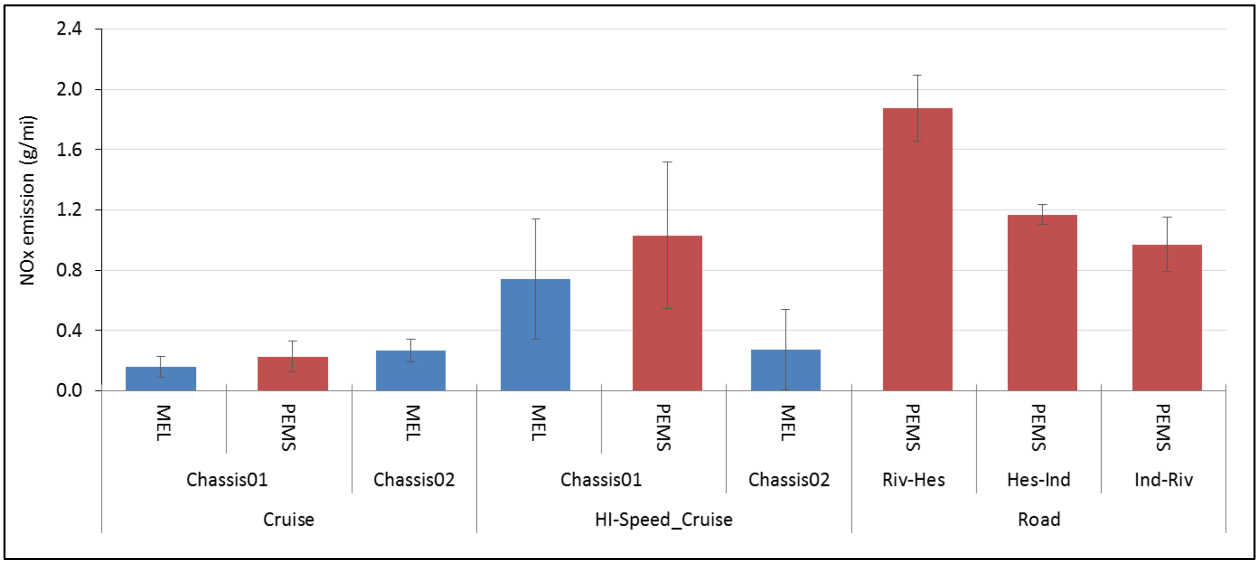


Figure 4-3 Average NOx Emissions on a g/bhp-hr Basis for the Freeway and SET cycles for the Manufacturer A Truck (top) and Manufacturer B Truck (bottom)



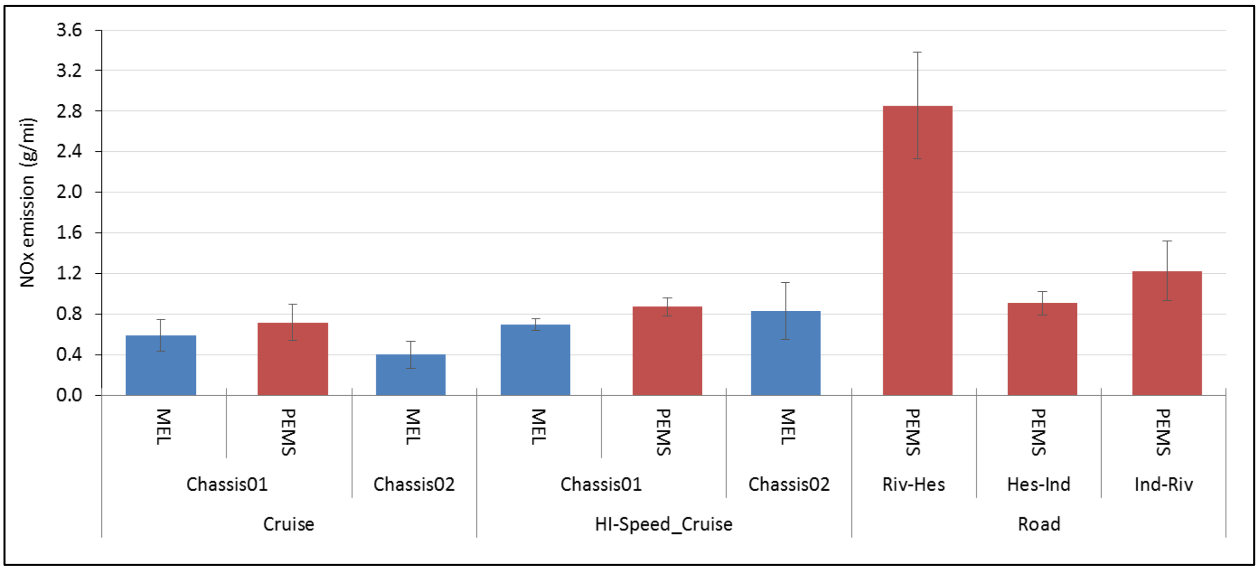


Figure 4-4. Average NOx Emissions on a g/mi Basis for the Freeway and SET cycles for the Manufacturer A Truck (top) and Manufacturer B Truck (bottom)

The results of this study can also be compared to results from previous and on-going studies. Jiang et al. (2018) measured UDDS NOx emission rates for four MY 2012 or newer HDDVs with the low mileages (<30,000miles). The NOx mission ranged from 0.14 and 0.39 g/bhp-hr over the UDDS cycle, which was consistent with the 0.39 g/bhp-hr emission rate for the Manufacturer B truck tested in this study. The UDDS NOx emission rate of 0.82 g/bhp-hr for the Manufacturer A truck was much higher than the range reported by the EMA study. Other studies have indicated that some heavy-duty vehicles have higher emission rates. Thiruvengadam et al. (2015) found slightly higher UDDS NOx emissions of 1.28 and 2.07 g/bhp-hr for two SCR equipped HDDVs. More recently, CARB has collected information from a range of different trucks as part of a Truck and Bus Surveillance study. This included data on 20 trucks that was used to updated the EMFAC2017 (CARB, 2018). The vehicles from this study showed a with range of emission rates, with some comparable to the 0.2 g/bhp-hr standard over the UDDS, but with many vehicles with higher emission rates ranging from 1 to over 2 g/bhp-hr (CARB, 2017; Quiros et al., 2017).

For SCR-equipped vehicles, NOx emissions are typically strongly correlated to the SCR temperature. Specifically, a minimum exhaust temperature is needed to promote hydrolysis of urea into ammonia (NH_3), which then reduces NOx into nitrogen (N_2) and water (H_2O) (Majewski, 2006). That requisite conversion temperature is typically around 250°C for more optimal conversion. The SCR inlet temperatures for all vehicles in this study is provided in Figure 4-1 for the urban driving cycles and Figure 4-3 for the freeway driving cycles. For the urban driving cycles for the Manufacturer A truck, all the hot start cycles had average SCR inlet temperatures above 250°C, except for the UDDS cycle for the second chassis dynamometer test, on-road UDDS and the transient cycles for the engine dynamometer and the second chassis dynamometer tests.

For the Manufacturer A truck, the average SCR inlet temperatures for the cold start cycles ranged from 217 to 240°C, which was comparable to the range of 222 to 269°C for the hot start UDDS and FTP cycles for both chassis dynamometer testing and engine dynamometer testing. When examining the real-time SCR temperature for the cold start UDDS Cycle (Figure 4-5), the SCR temperature increased to above 250°C after the second hill at about 450 seconds, which contributed its relatively high average SCR inlet temperature of the cycle, although the initial SCR temperature was below 50°C. For the Manufacturer B truck for the urban driving cycles, only the hot start UDDS cycles of the first chassis dynamometer testing had average SCR temperatures above 250°C. The average SCR inlet temperatures of the cold start cycles ranged from 165 to 182°C, which was much lower than the range of 199 to 275°C for the hot start UDDS cycles for the chassis dynamometer testing for the Manufacturer B truck. For the freeway driving cycles, the results show that the average SCR inlet temperature is at or above 250°C for the Cruise, HHDDT-S cycles, on-road driving cycles, and RMC cycles of the engine dynamometer testing for both vehicles.

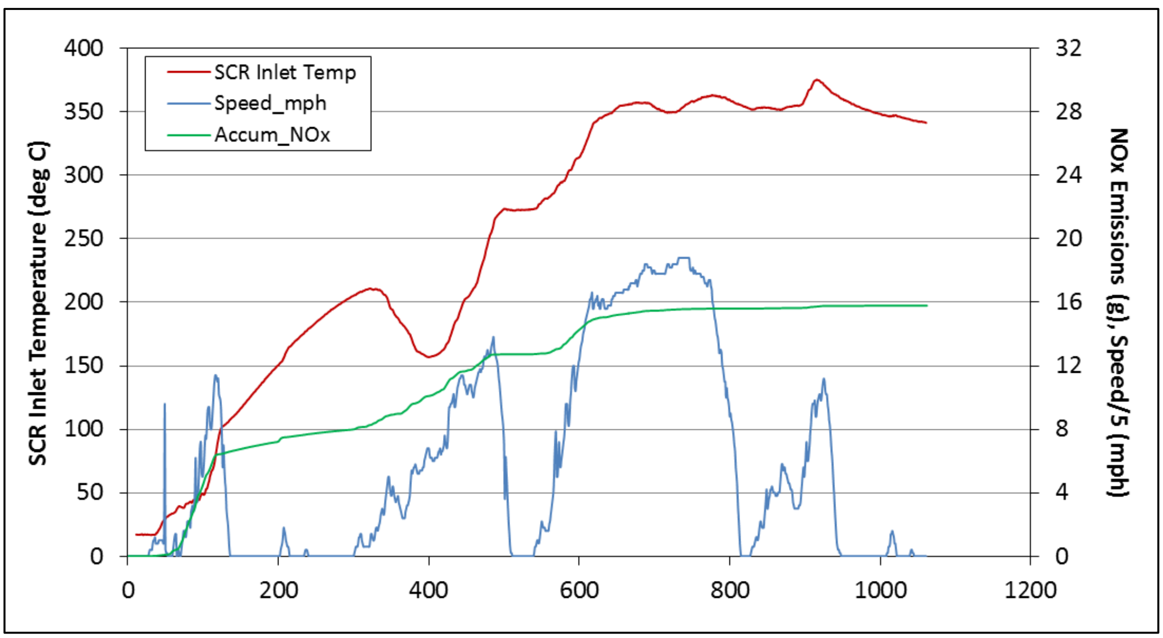
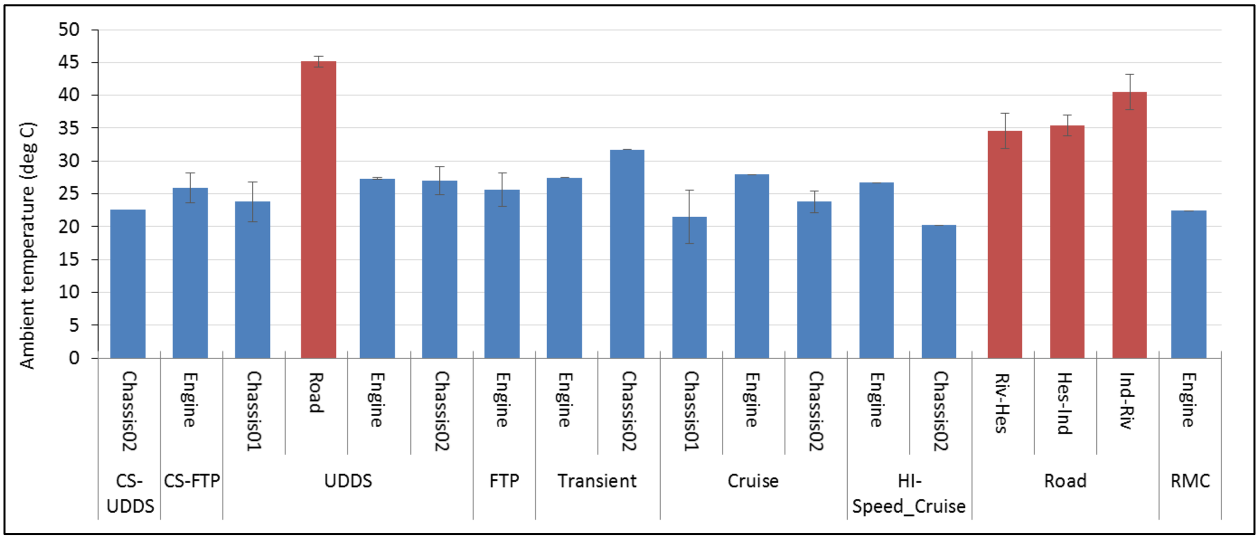


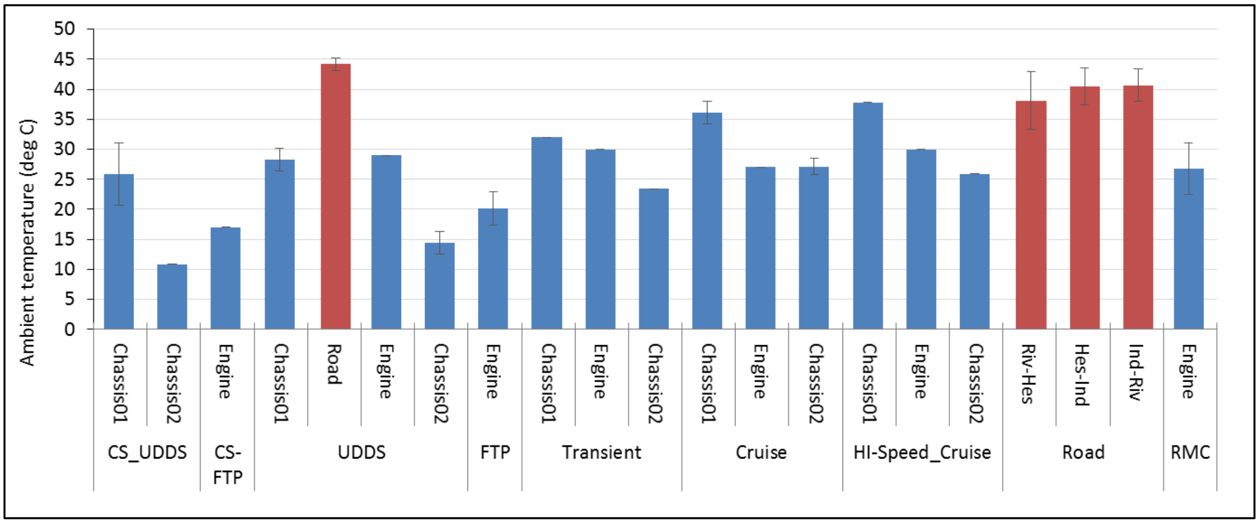
Figure 4-5 Real-time SCR temperature for the cold start UDDS Cycle of the first Chassis dynamometer testing for the Manufacturer A Truck

4.1.1.2 Testing Temperature Conditions

Ambient temperature: Figure 4-6 shows the ambient temperatures of all test conditions for the Manufacturer A and Manufacturer B trucks, respectively. The initial and final chassis dynamometer tests are denoted Chassis 01 and Chassis 02, respectively. The UDDS Chassis 01 and 02 ambient temperatures were comparable to those of the engine dynamometer, with the exception of Chassis 02 for the Manufacturer B truck. The highest ambient temperatures for the Manufacturer A and B truck testing were found for the on-road testing. The ambient temperatures for the on-road testing for both vehicles were matched with the local temperatures for Indio.



Note that the ambient temperatures for engine dynamometer are the temperatures of air going into intake air manifold.



Note that the ambient temperatures for engine dynamometer are the temperatures of air going into intake air manifold.

Figure 4-6 Ambient temperature for the Manufacturer A Truck (top) and Manufacturer B Truck (bottom)

Coolant temperature: Figure 4-7 provides the coolant temperatures of all test conditions for the Manufacturer A and Manufacturer B trucks, respectively. Overall, there were not significant differences in coolant temperature between different test conditions, with the exception of the cold start tests, although the coolant temperatures for a few tests were near 100˚C. The coolant temperatures ranged from 82 to 100˚C for the hot start/running tests, and from 62 to 69˚C for the cold start tests.

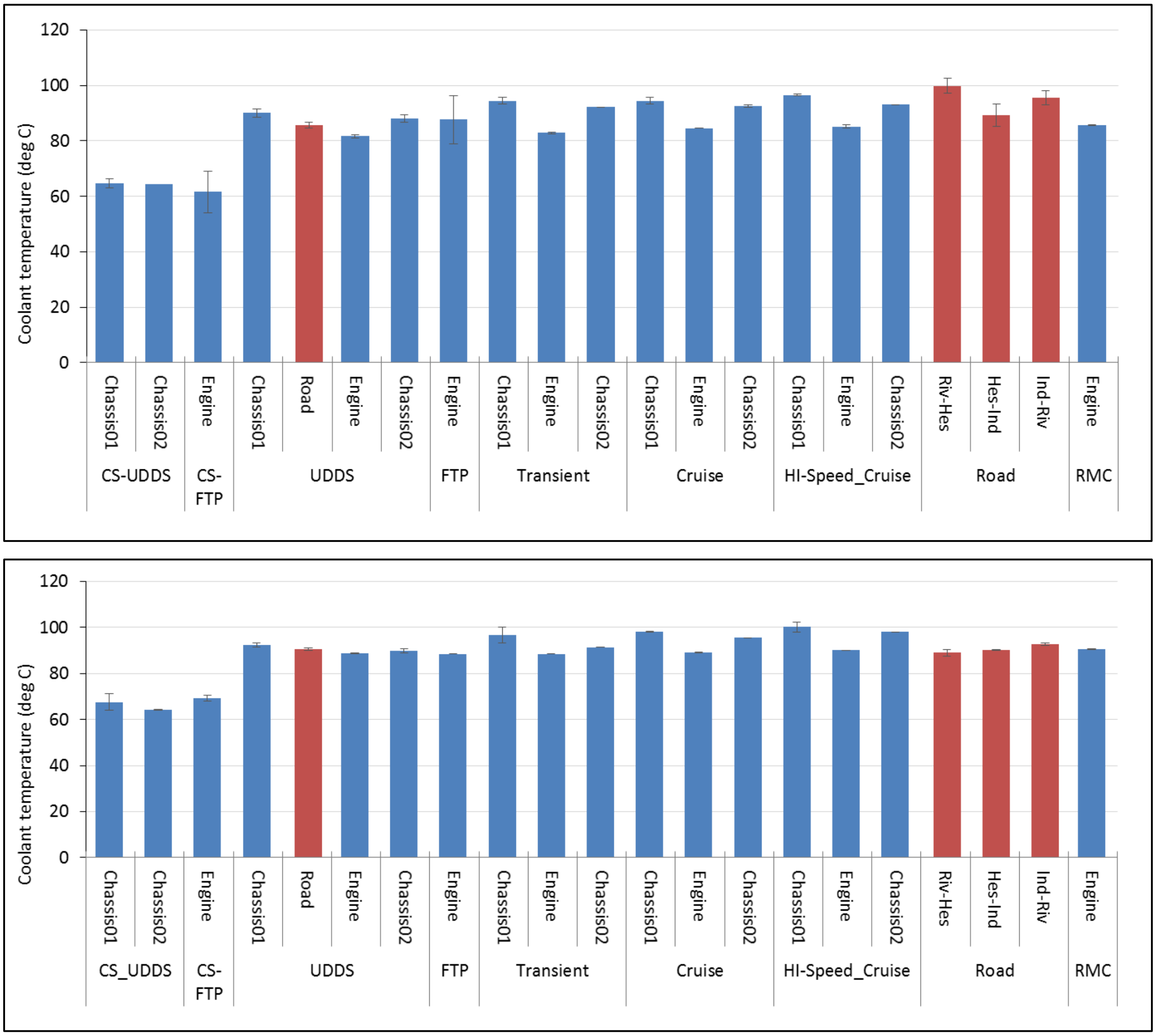
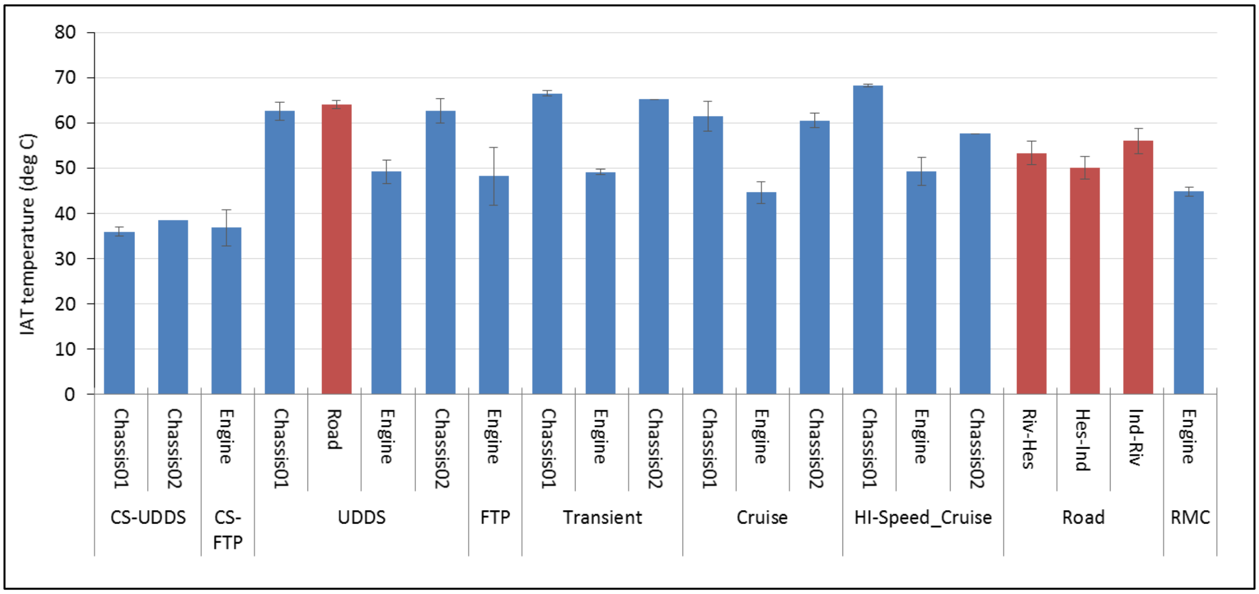


Figure 4-7 Coolant temperature for the Manufacturer A Truck (top) and Manufacturer B Truck (bottom)

Intake air manifold temperature (IAT): Figure 4-8 shows the IATs of all test conditions for the Manufacturer A and Manufacturer B trucks, respectively. The engine dynamometer testing had the lowest IATs, which ranged from 36 to 49˚C. The IAT temperature for the chassis dynamometer were higher than those for the engine dynamometer testing, ranging from 48 to 67˚C.



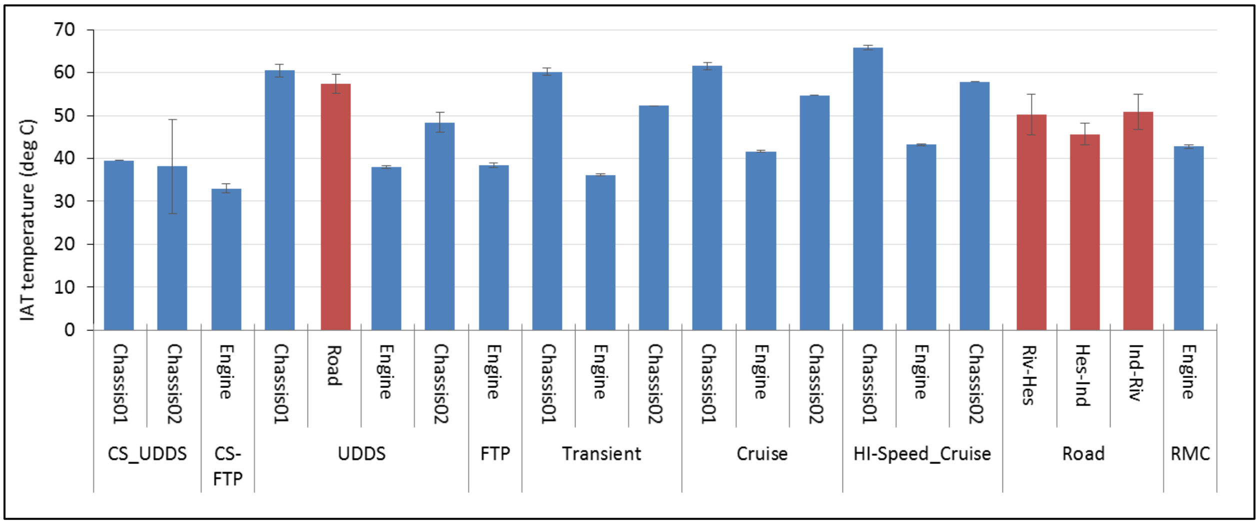


Figure 4-8 Intake air manifold temperature for the Manufacturer A Truck (top) and Manufacturer B Truck (bottom)

4.1.2 UDDS NOx emission differences between the different testing conditions

4.1.2.1 Cycle differences between various driving schedules

In order to understand the differences in test cycles between the different testing conditions for the same cycle, plots of cumulative power, torque and rpm for the UDDS chassis dynamometer and engine dynamometer cycles using ECM data are shown in Figure 4-9 to Figure 4-11 for the Manufacturer A truck and Figure 4-12 to Figure 4-14 for the Manufacturer B truck. The comparisons of engine rpm and torque points from all the tests (including engine dynamometer cycles, chassis dynamometer cycles, and on-road tests) are provided in Appendix I for both vehicles.

For the Manufacturer A engine, good agreement in cumulative power was found between the UDDS chassis and engine dynamometer cycles, with the cycle power around 23 bhp-hr, as shown in Figure 4-9. Similar torque profiles were also observed between chassis and engine dynamometer. In terms of rpm, the engine dynamometer tests had slightly lower rpm (~5%) because the governed speed on the engine dynamometer was slightly lower than that for the chassis dynamometer. As discussed above, the most significant difference in engine operation for the Manufacturer A engine was the cold start mode operation for the engine dynamometer testing.

For the Manufacturer B engine, a good agreement in cumulative power was found between UDDS chassis and engine dynamometer cycles with engine dynamometer cycles having slightly higher power, as shown in Figure 4-12. This was a consequence of the higher idle speed used for the engine dynamometer. The torque profiles were found to be similar between the chassis and engine dynamometer.

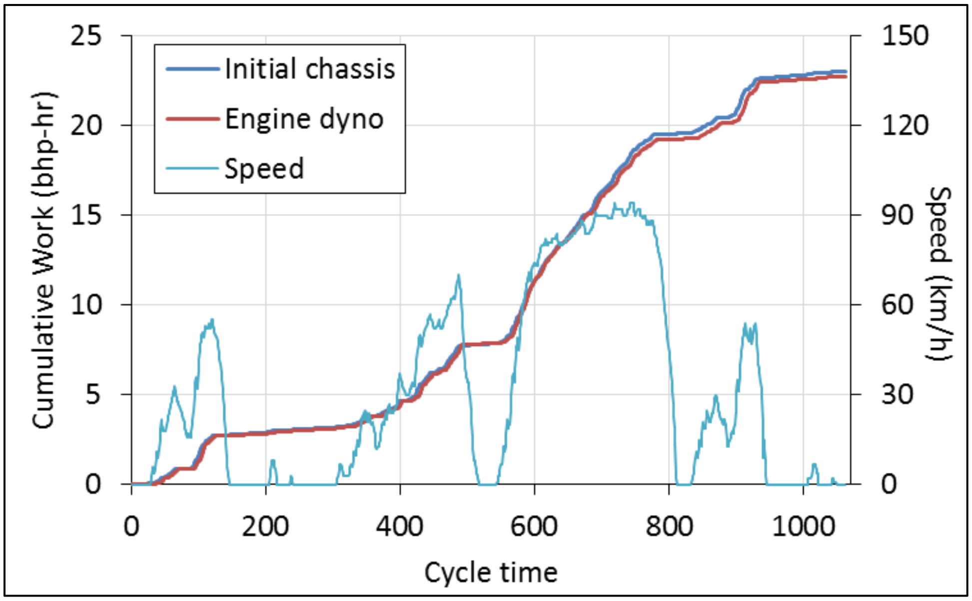


Figure 4-9 Cumulative power between initial chassis UDDS and engine dynamometer UDDS for Manufacturer A Engine

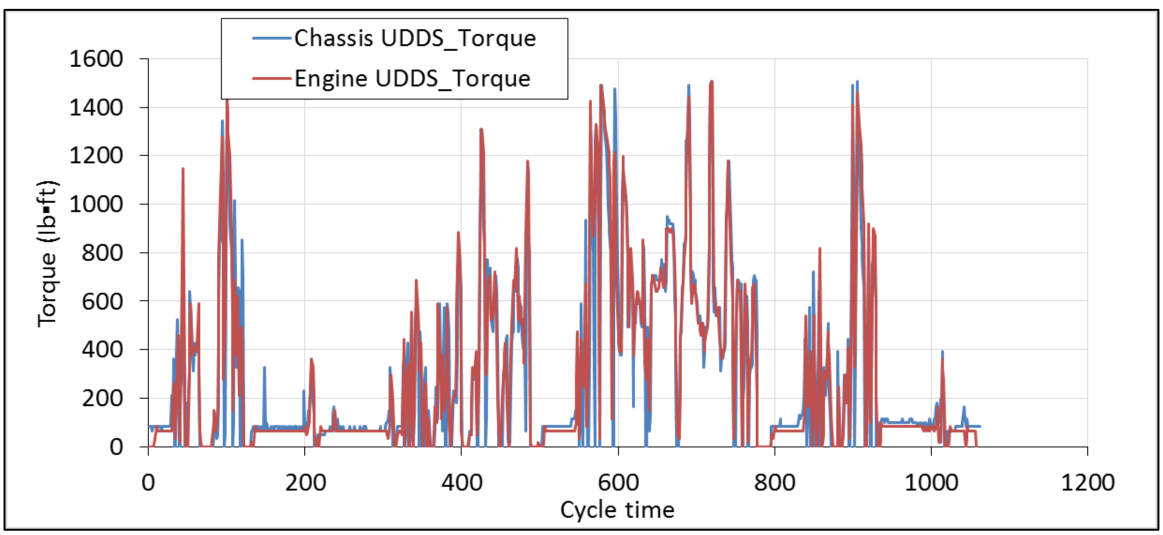
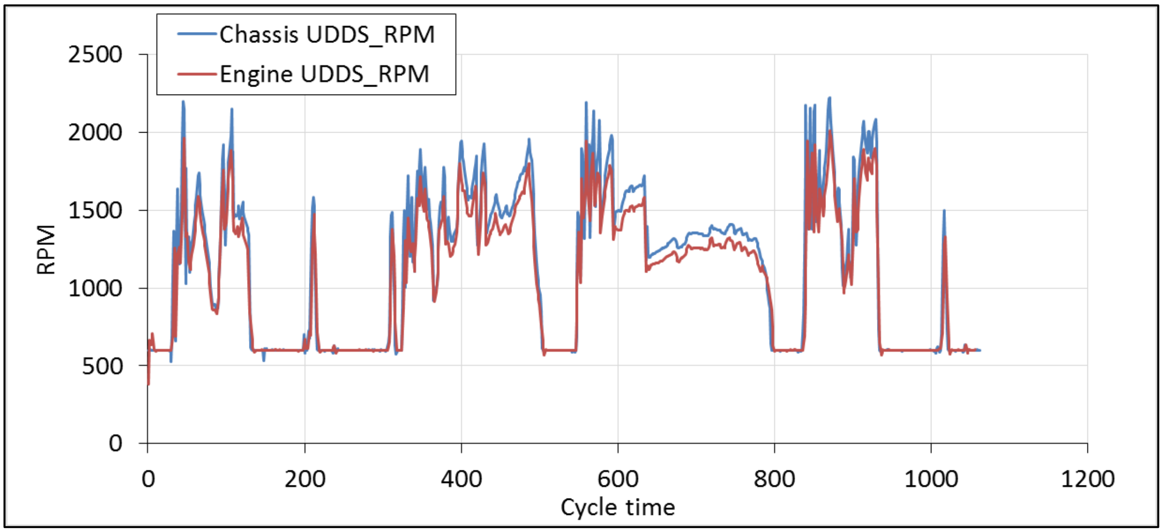


Figure 4-10 Torque between initial chassis UDDS and engine dynamometer UDDS for Manufacturer A Engine



Note that the governed speed of engine dynamometer was 2000 and the governed speed of chassis dynamometer was 2100.

Figure 4-11 rpm between initial chassis UDDS and engine dynamometer UDDS for Manufacturer A Engine

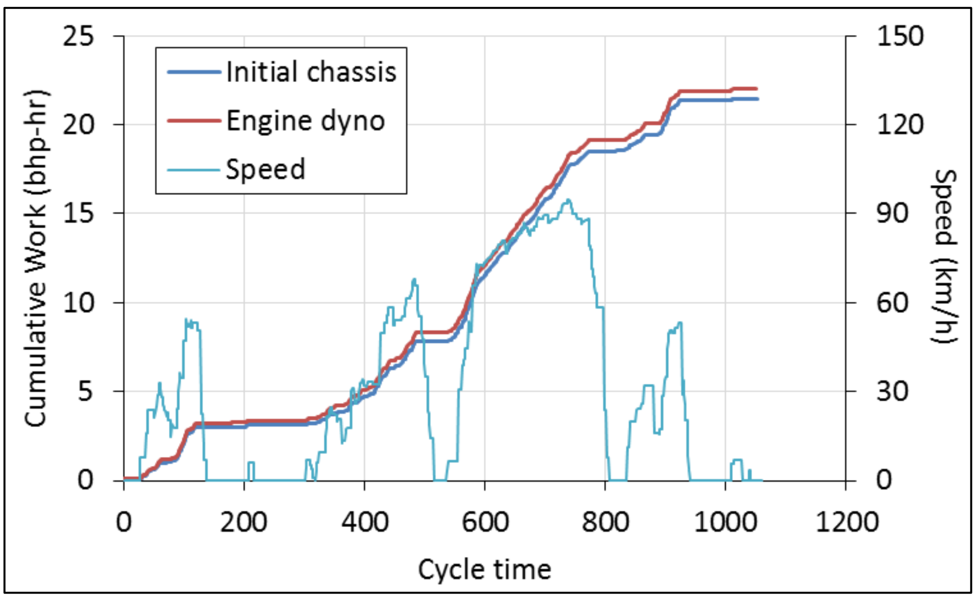


Figure 4-12 Cumulative power between initial chassis UDDS and engine dynamometer UDDS for Manufacturer B Engine

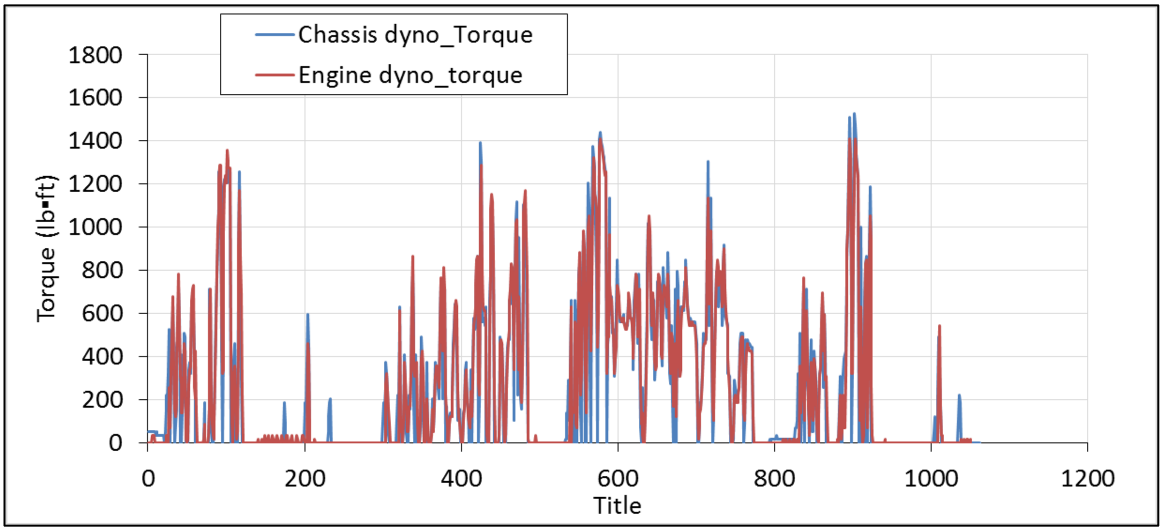
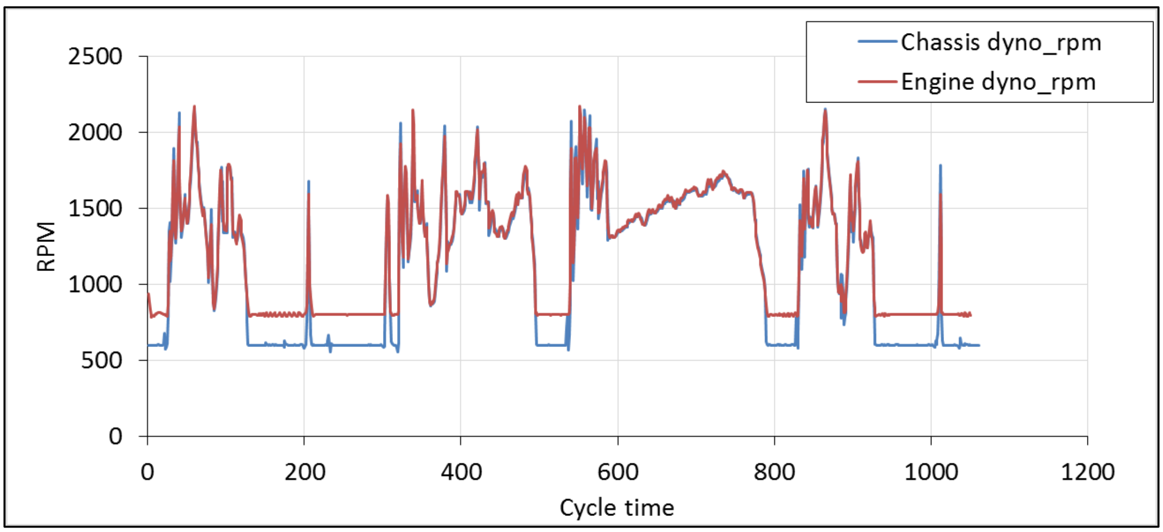


Figure 4-13 Torque between initial chassis UDDS and engine dynamometer UDDS for Manufacturer B Engine



Note that the idle speed of engine dynamometer was 850 and the idle speed of chassis dynamometer was 650. This difference in idle emissions has a minimal impact on the total integrated emissions, as emissions for the idle segments of the cycle are very low.

Figure 4-14 rpm between initial chassis UDDS and engine dynamometer UDDS for Manufacturer B Engine

4.1.2.2 SCR inlet temperature impact

In order to understand the impact of SCR inlet temperature on NOx emissions between the different testing conditions for the same cycle, plots of NOx emission rates on a g/bhp-hr basis and percent time for SCR inlet temperature >250°C for the UDDS chassis dynamometer, on-road and engine dynamometer cycles are shown in Figure 4-15 and Figure 4-17 for Manufacturer A and Manufacturer B, respectively. Since the operational temperature of SCR is typically around 250°C, conditions where the SCR inlet temperature is >250°C are expected to have high SCR conversion efficiencies. For the Manufacturer A truck, the engine dynamometer had the lowest NOx emission rate on a g/bhp-hr basis, while the results for some of the chassis dynamometer and on-road testing were over double of the values from the engine dynamometer. The NOx emission rate for Manufacturer A was lowest for the engine dynamometer testing, which is consistent with the engine dynamometer testing having the highest percent of time with the SCR inlet temperature >250°C. The on-road and second chassis dynamometer testing showed NOx emission rates more than twice those of the engine dynamometer testing, but also had a much lower percent time for SCR inlet temperature >250°C. Although the initial chassis dynamometer testing had the highest NOx emission rate, the percent time for SCR inlet temperature >250°C for this testing was in the middle for the range for the other tests.

In order to further understand the differences in NOx emission between the first Chassis dynamometer testing and the engine dynamometer testing, plots of cumulative NOx emissions and real-time SCR inlet temperature for the UDDS chassis dynamometer and engine dynamometer cycles are shown in Figure 4-16. The results show very similar NOx emissions for the first 350 seconds. The primary differences in NOx emissions for the UDDS occur between 350 and 700 seconds. During this time period, the NOx emissions were considerably higher for the chassis dynamometer testing, even though the SCR inlet temperatures were above 250°C for the chassis dynamometer testing. As discussed above, for the Manufacturer A truck, the lower emissions for the engine dynamometer testing was attributed to the engine running in a cold-start mode, which resulted in retarded injection timing.

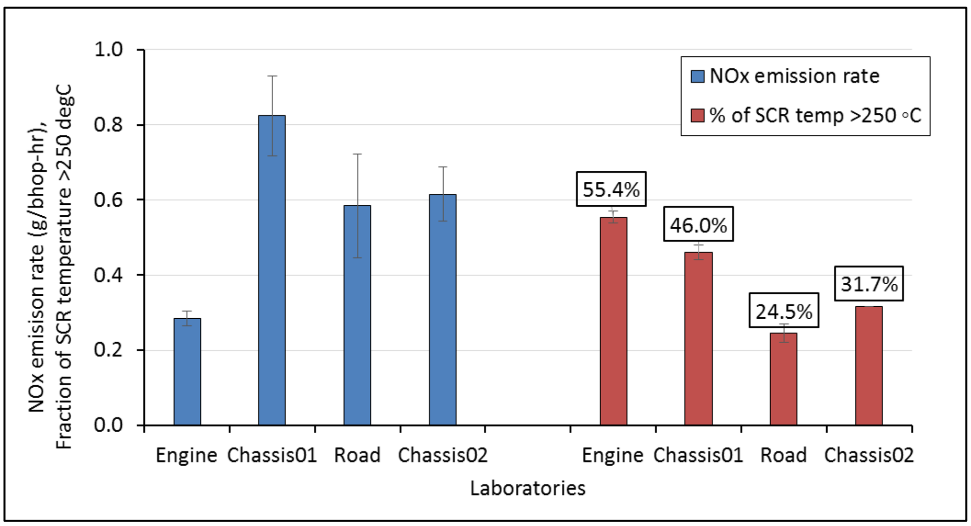


Figure 4-15 NO_x emissions for UDDS cycle and percent time for SCR inlet temperature >250°C between the different laboratories for the Manufacturer A truck

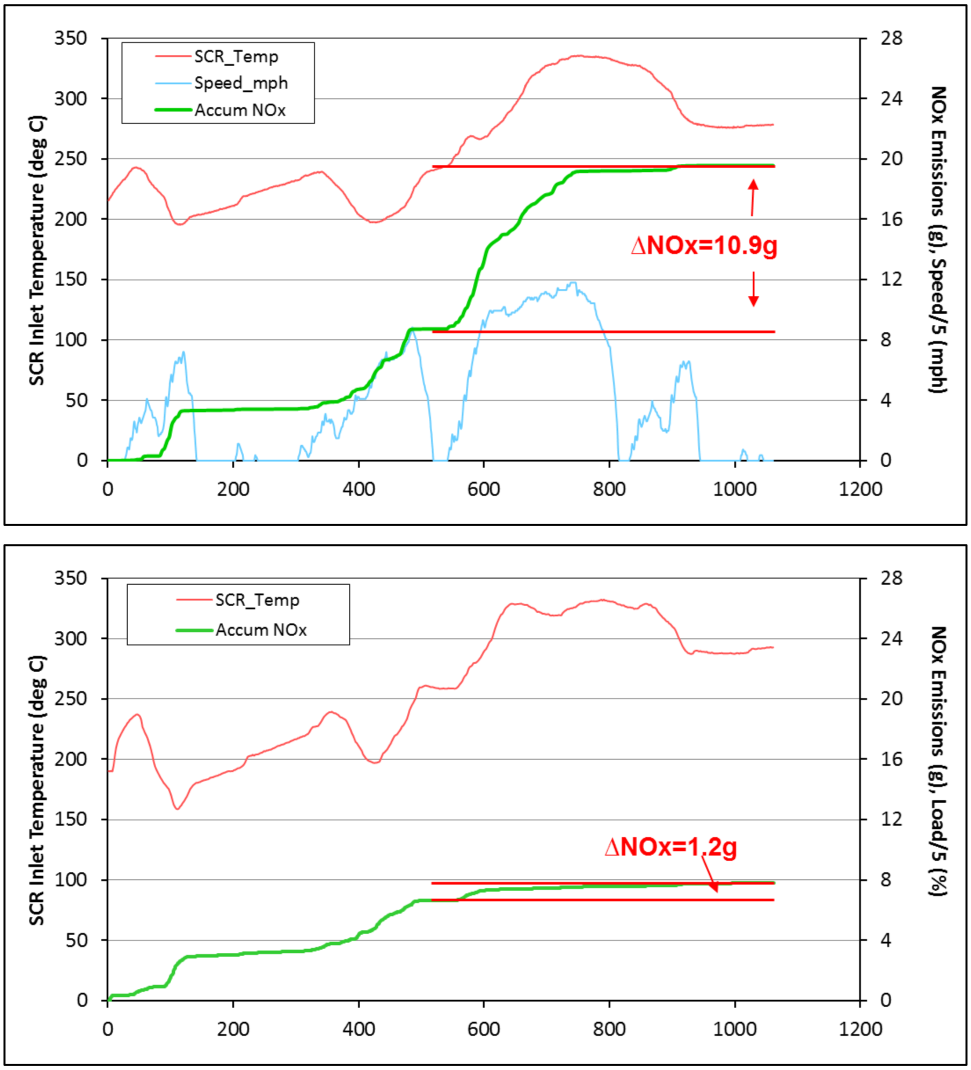


Figure 4-16 Cumulative NOx emissions for the UDDS Cycle of the first Chassis dynamometer testing (top) and the engine dynamometer testing (bottom) for the Manufacturer A Truck

Similar trends were observed from the Manufacturer B truck with the engine dynamometer having the lowest NOx emission rate on a g/bhp-hr basis. The on-road testing had NOx emission rates comparable to those for the engine dynamometer testing, which was consistent with the similar percent time for SCR inlet temperature >250°C between two testing conditions. The NOx emission rates for both chassis dynamometer test rounds were much higher than those of the engine dynamometer or on-road testing, even though the highest percent time for SCR inlet temperature >250°C was found for the initial chassis dynamometer testing, and only slight differences existed in percent time for SCR inlet temperature >250°C between the second chassis and engine dynamometer testing.

In order to understand the differences in NOx emission between the chassis dynamometer testing and the engine dynamometer testing, plots of cumulative NOx emissions and real-time SCR inlet temperature for the UDDS chassis dynamometer and engine dynamometer cycles are shown in Figure 4-18. The results show trends very similar to those observed from the Manufacturer A truck with comparable cumulative NOx emissions for the first 350 seconds. The largest differences in NOx emissions for the UDDS occur between 400 and 600 seconds. During this time period, the

NOx emissions were relatively higher for the chassis dynamometer testing than engine dynamometer, even though the SCR inlet temperatures were lower of engine dynamometer.

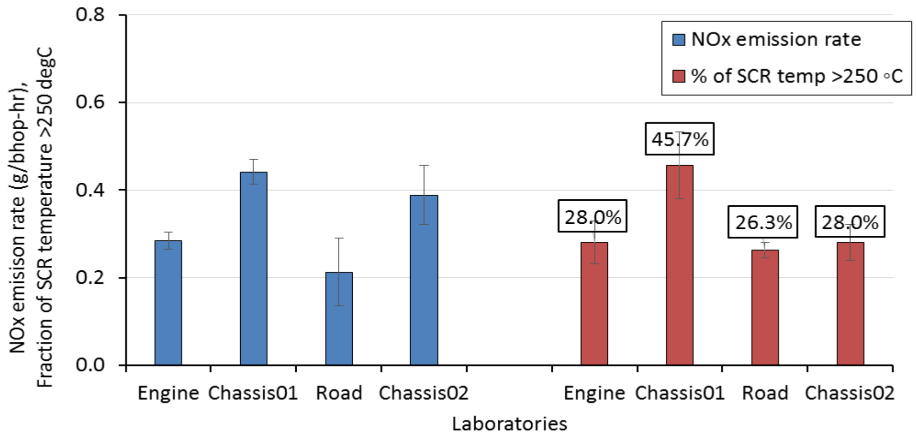


Figure 4-17 NO_x emissions for UDDS cycle and percent time for SCR inlet temperature >250°C between the different laboratories for the Manufacturer B truck

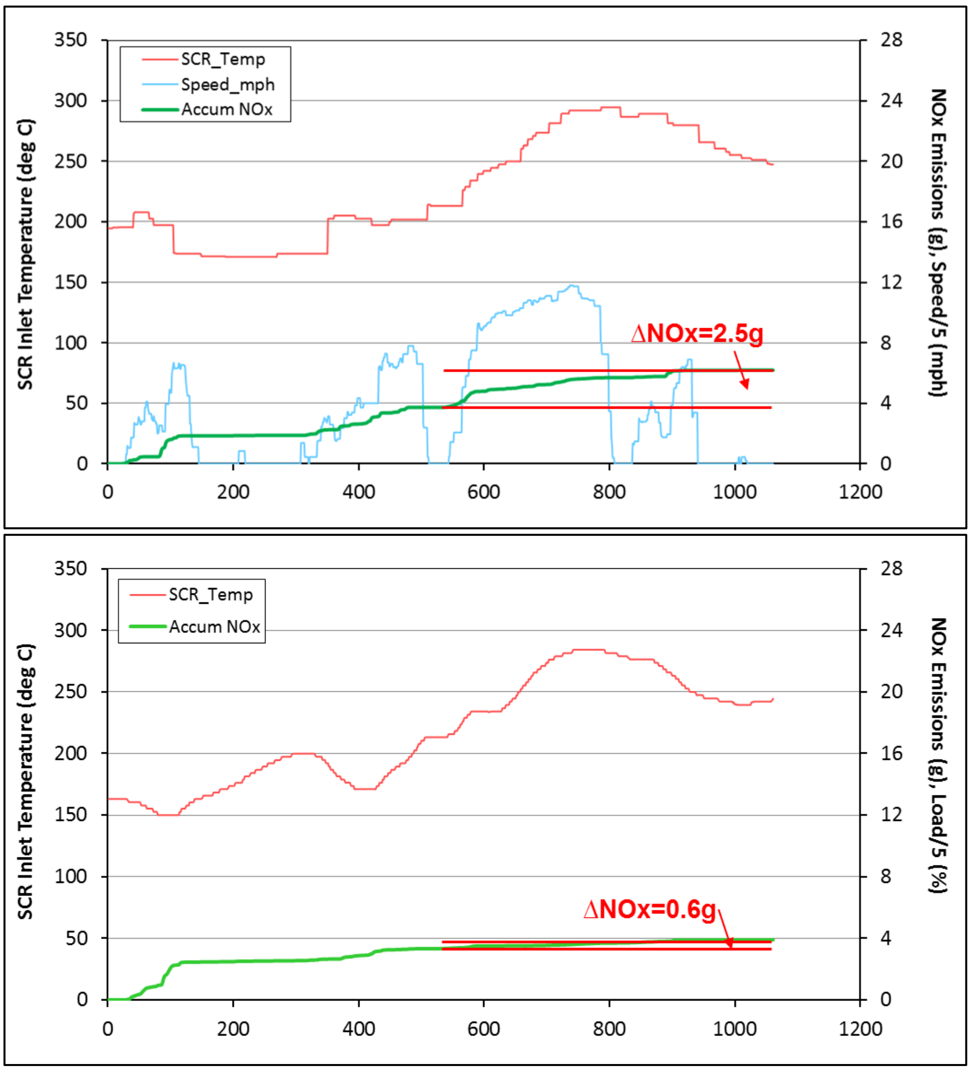


Figure 4-18 Cumulative NOx emissions for the UDDS Cycle for the first Chassis dynamometer testing for the Manufacturer A Truck (top) and Manufacturer B Truck (bottom)

For SCR-equipped vehicles, NOx emissions are typically strongly correlated to the SCR temperature. A number of studies have shown that the freeway driving cycles with the higher average SCR temperatures had much lower NOx emission rates compared to the transient cycles, such as the UDDS and CARB-transient, which was also consistent with the results in section 4.1.1 of our study (CARB, 2017; Quiros et al., 2017; Jiang et al., 2018).

4.1.2.3 Engine out NOx emissions impact

In order to further analyze the factors that may be responsible for the differences in NOx emissions between chassis dynamometer and engine dynamometer testing, Figure 4-19 and Figure 4-20 show a comparison of engine out and SCR out UDDS NOx emissions on a concentration basis between two laboratories for Manufacturer A and Manufacturer B, respectively. Note that some portion of the cycles for the Manufacturer A truck and some full cycles for the Manufacturer B truck didn't have valid engine out NOx emission readings due to NOx sensors being below their activation temperature of 250°C for Manufacturer B and 190°C for Manufacturer A. As the rpm and torque for the engine dynamometer version UDDS were obtained from one of the three initial chassis dynamometer UDDS tests. It was expected the performance of the engine was similar between two tests. However, engine out NOx emissions for the chassis dynamometer test were found to be much higher than those for the engine dynamometer test for both vehicles, especially between 500 to 800 seconds, which was the high speed portion of UDDS cycle. The SCR out NOx emissions for the chassis dynamometer test were also observed to be higher than those of the engine dynamometer test. As discussed before, the largest difference in cumulative NOx emissions between the chassis and engine dynamometer testing was from NOx emissions generated around 500 to 800 seconds (Figure 4-16 and Figure 4-18), where higher concentrations of engine out and SCR out NOx were also observed for chassis dynamometer testing. As discussed above, the lower emissions for the engine dynamometer testing can be attributed to retarded fuel injection timing for the engine dynamometer testing that Manufacturer A suggested was due to the engine operating in a cold start mode.

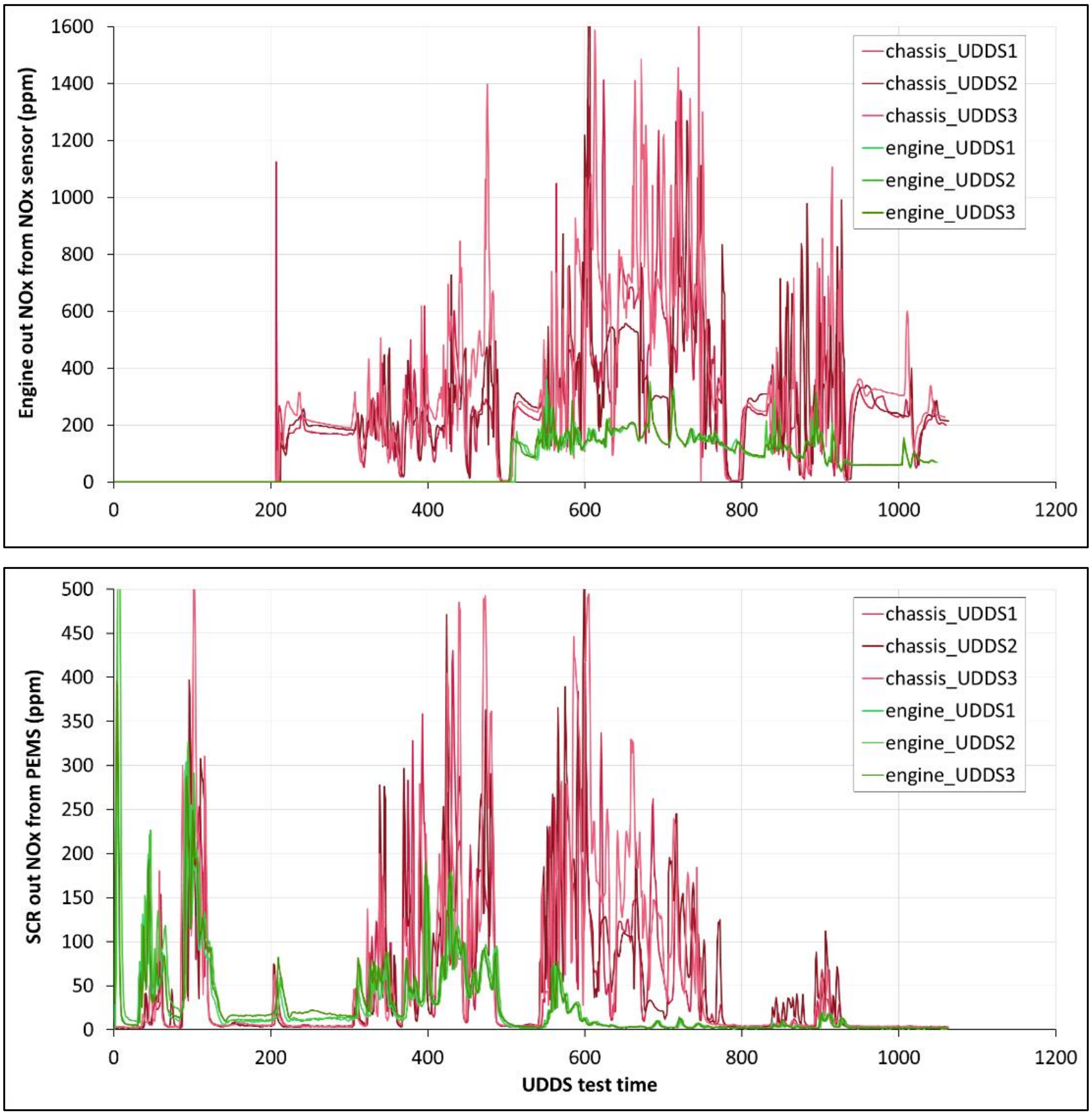


Figure 4-19 Comparison of engine out and SCR out NOx emission on a PPM basis from ECM of UDDS chassis dynamometer and engine dynamometer test for the Manufacturer A truck

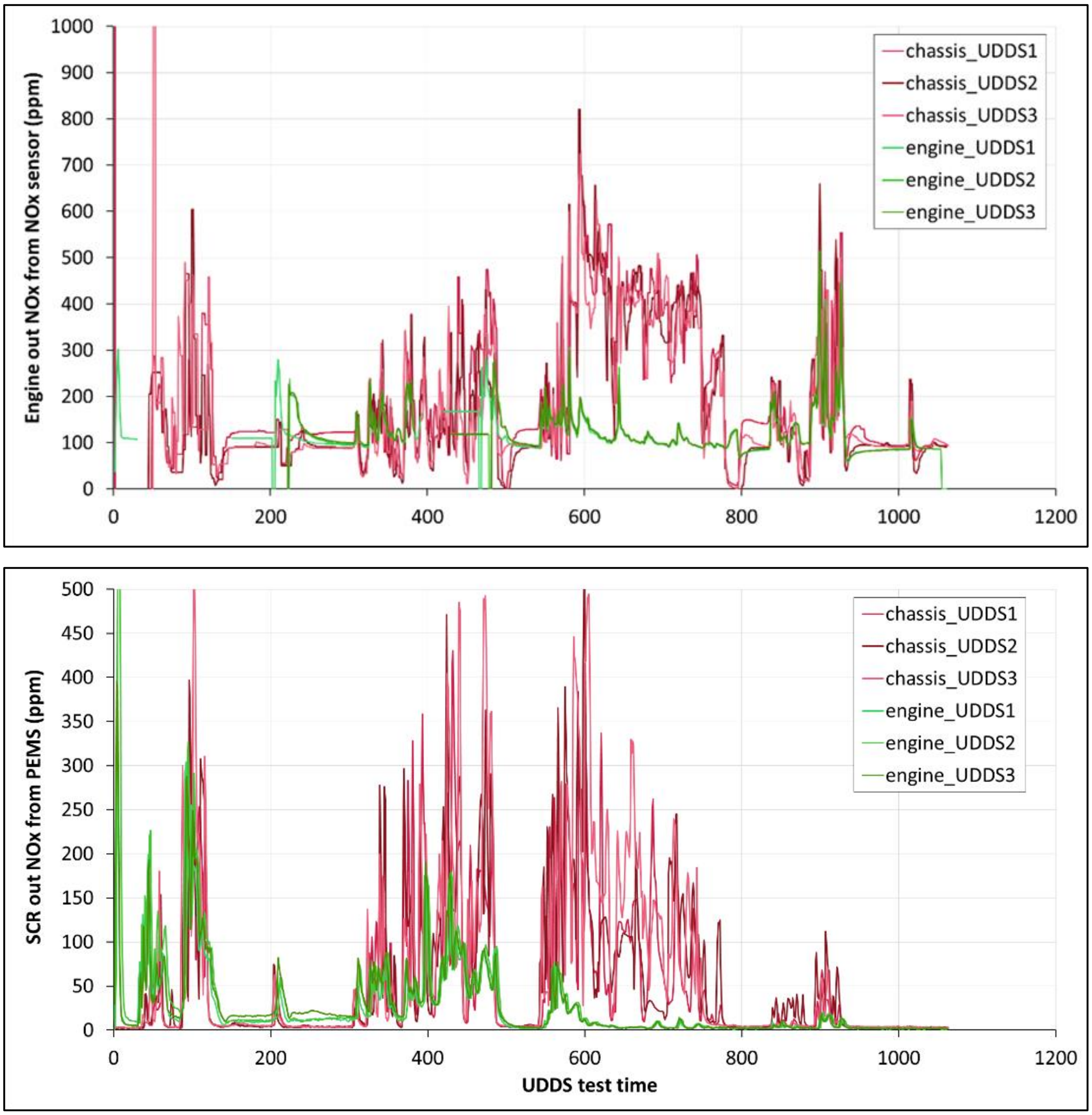


Figure 4-20 Comparison of engine out and SCR out NOx emission on a PPM basis from ECM of UDDS chassis dynamometer and engine dynamometer test for the Manufacturer B truck

It is well know that NOx emissions are linked to injection timing and its impact on combustion and combustion temperatures[14]. As discussed above, retarded fuel injection timing was observed for the engine dynamometer for the Manufacturer A engine, which would have contributed to lower NOx emissions. Further analysis was conducted on the fuel rate and fuel injection timing, as shown in Figure 4-21 for the Manufacturer A truck and Figure 4-22 for the Manufacturer B truck. Note fuel injection timing data was generally not available for the Manufacturer B truck, and when available, the frequency of fuel rate data wasn't 1 hz (~5 seconds per data). Figure 4-21 shows the fuel injection timing for the UDDS for the engine dynamometer testing compared to the chassis dynamometer testing. The observation of lower fuel consumption rates and CO_2 emissions during the chassis dynamometer testing compared to the engine dynamometer testing is also consistent with the retarded injection timing found for the Manufacturer A truck, as shown in Table

[14] Heywood, J.B., 1988. Internal combustion engine fundamentals.

4-1 and Figure 4-53, respectively. Interestingly, the Manufacturer A engine was found to have advanced fuel injection timing during the beginning of the cold start FTP cycle before switching to retarded fuel injection timing around 550s. When the vehicle was tested on chassis dynamometer, the fuel injection timing was always advanced during the cold start UDDS cycle. Although the fuel timing and fuel rate for the engine dynamometer for the Manufacturer B truck were not available, trends similar to those seen for the Manufacturer A truck were observed for the Manufacturer B truck, with higher engine out NOx and lower CO_2 emissions for the chassis dynamometer testing.

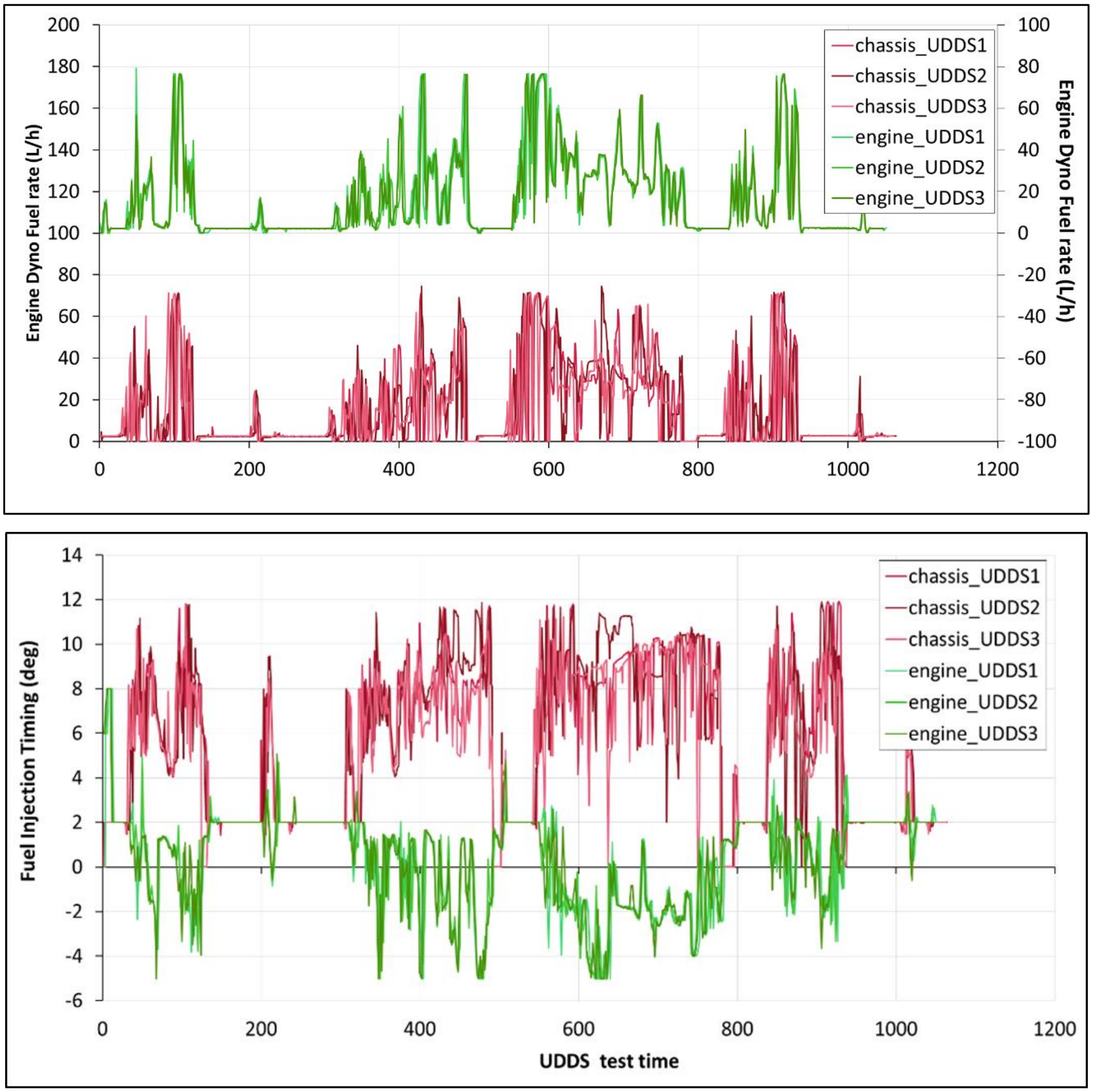


Figure 4-21 Fuel rate and fuel injection timing from ECM of UDDS chassis dynamometer and engine dynamometer test for the Manufacturer A truck

Table 4-1 Comparison of fuel consumption from ECM of UDDS chassis dynamometer and engine dynamometer test for the Manufacturer A truck

Cycle ID	Fuel consumption (liter/cycle)		% Difference
	Chassis dynamometer test	Engine dynamometer test	
UDDS1	4.41	4.78	
UDDS2	4.59	4.71	
UDDS3	4.24	4.76	
Ave	4.41	4.75	7%

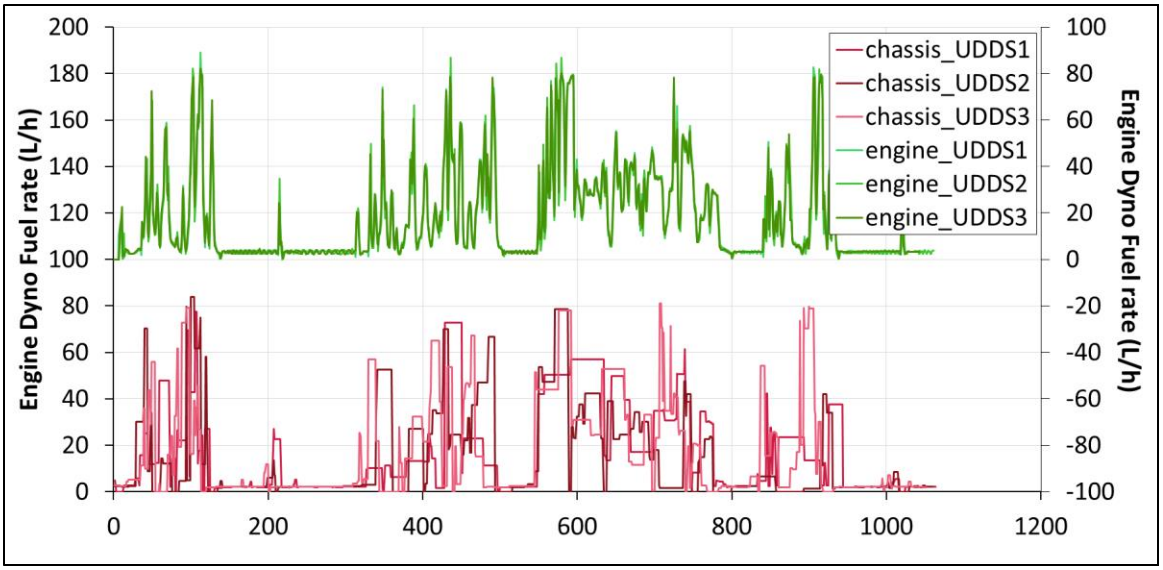
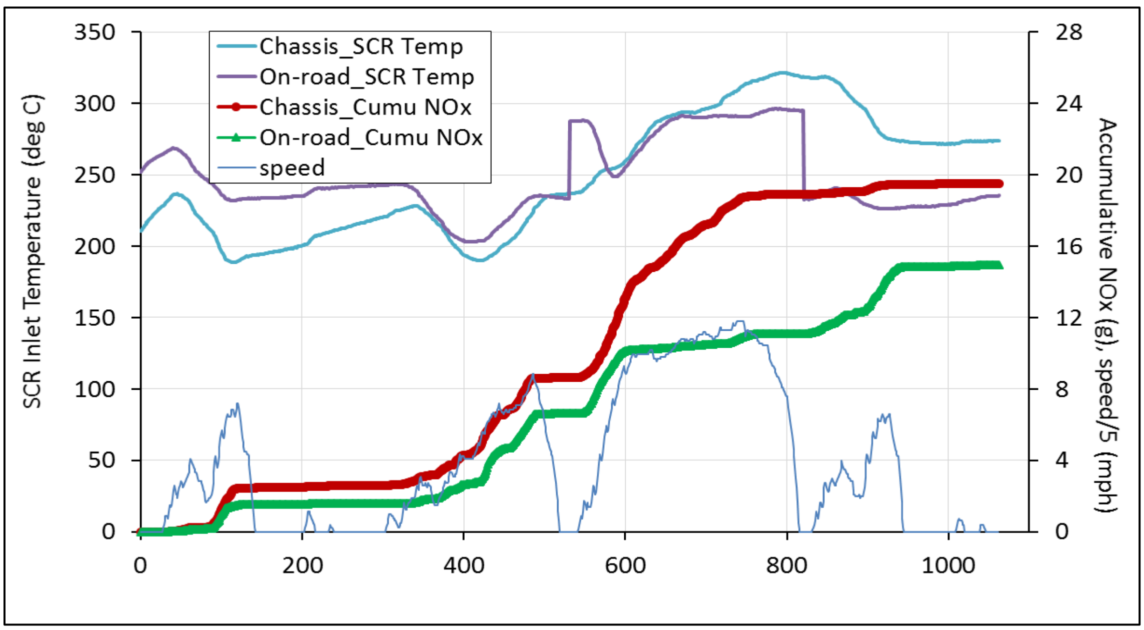


Figure 4-22 Fuel rate from ECM of UDDS chassis dynamometer and engine dynamometer test for the Manufacturer B truck

4.1.2.4 <u>UDDS NOx emission differences between the chassis dynamometer and on-road testing</u>

The NOx emissions for the chassis dynamometer and on-road tests can also be compared. For both trucks, NOx emissions for the on-road testing were also lower than those for the chassis dynamometer, as shown in Figure 4-15 and Figure 4-17 for Manufacturer A and Manufacturer B, respectively. Note that the on-road UDDS was not a continuous test. The three segments of on-road testing were not in the same order as in the chassis UDDS. The order was shown in the Figure 4-23 (M2-M1-M3). These differences cannot be attributed to differences in fuel timing, however, as the fuel timing values for the chassis dynamometer and on-road testing were similar. In order to further understand the differences in NOx emission between the first Chassis dynamometer and the on-road testing, plots of cumulative NOx emissions and real-time SCR inlet temperature for the UDDS chassis dynamometer and on-road cycles are shown in Figure 4-23 and Figure 4-26 for Manufacturer A and Manufacturer B, respectively. As shown, the primary differences in NOx emissions for the UDDS occur around 500 seconds, with the NOx emissions being higher for the chassis dynamometer testing. For the Manufacturer A truck during this time period, the SCR inlet temperatures for the on-road testing were above 250°C for both tests, so the major differences in NOx emissions cannot be fully attributed to SCR temperature differences. When examining the engine out NOx for the Manufacturer A truck, the on-road UDDS had lower engine out NOx than for the chassis dynamometer UDDS around 500 to 800 seconds, although similar fuel timing was observed between the two test cycles. This is the main reason for the higher NOx emissions for the chassis dynamometer testing results compared to the on-road UDDS testing results. For the Manufacturer B truck, on the other hand, similar engine out NOx emissions were found between the on-road and chassis dynamometer tests, while the SCR inlet temperature for the on-road testing was higher than that for the chassis dynamometer testing, particularly in the 500 to 700 second range. This could be due to the long drive out to the site for the on-road testing, where the engine would have been operating for a considerably period of time under relatively warm conditions. As such, the SCR temperature and associated SCR efficiencies were lower during the period for the Manufacturer B truck for the chassis dynamometer testing, leading to higher tailpipe NOx emissions for the chassis dynamometer compared to the on-road testing. It should be noted that some differences were observed in the NOx emissions and SCR temperatures for the M3 portion of the cycle. The lower SCR temperatures for the M3 cycle for the on-road testing can be attributed to the fact that M3 cycle for the on-road testing was conducted after the M1 segment, which is less aggressive and achieves lower temperatures than the M2 segment of the cycle.



Note that the on-road UDDS was not a continuous test. Three segments of on-road testing were not in the same order as in the chassis UDDS. The order was shown in the figure below M2-M1-M3.

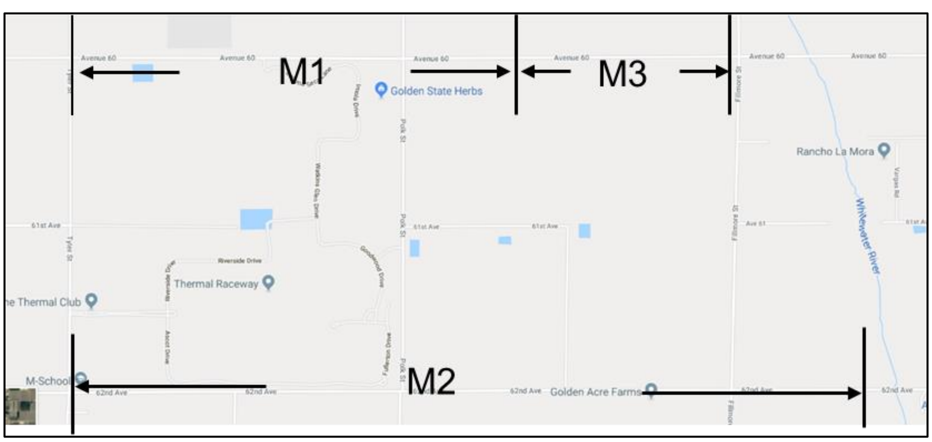


Figure 4-23 Comparison of SCR inlet temperature and accumulative Tailpipe NOx for the chassis dynamometer and on-road UDDS tests for the Manufacturer A truck

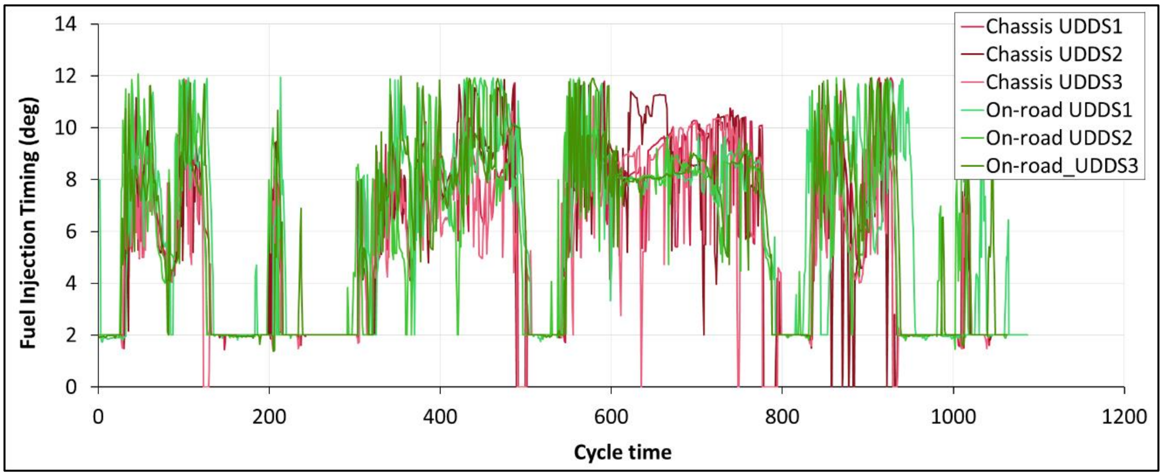


Figure 4-24 Comparison of fuel timing from ECM for the chassis dynamometer and on-road UDDS tests for the Manufacturer A truck

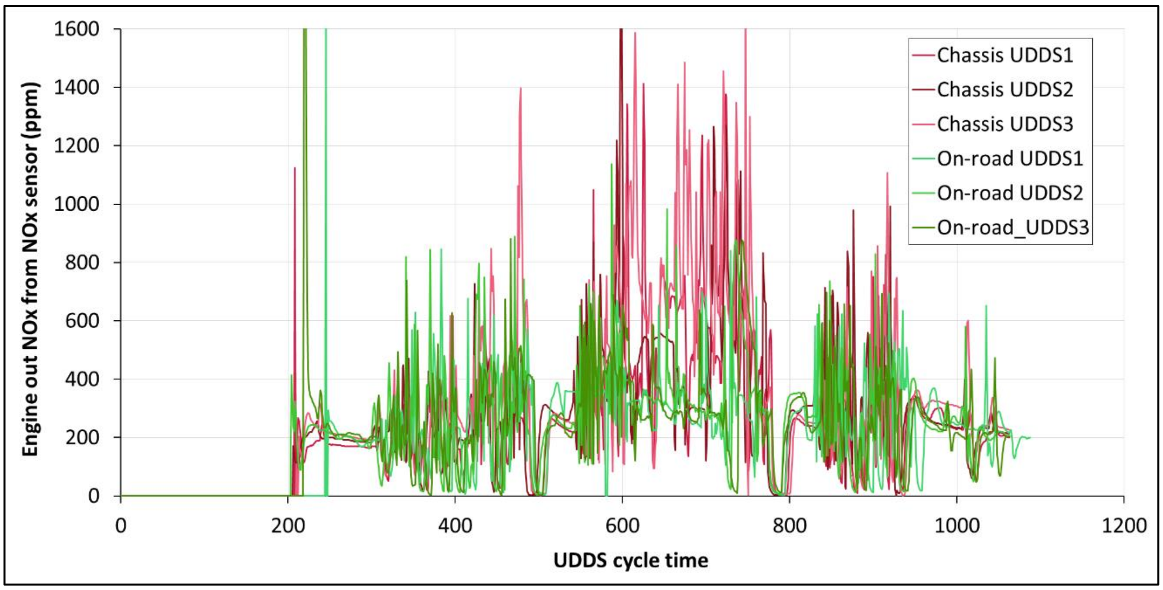
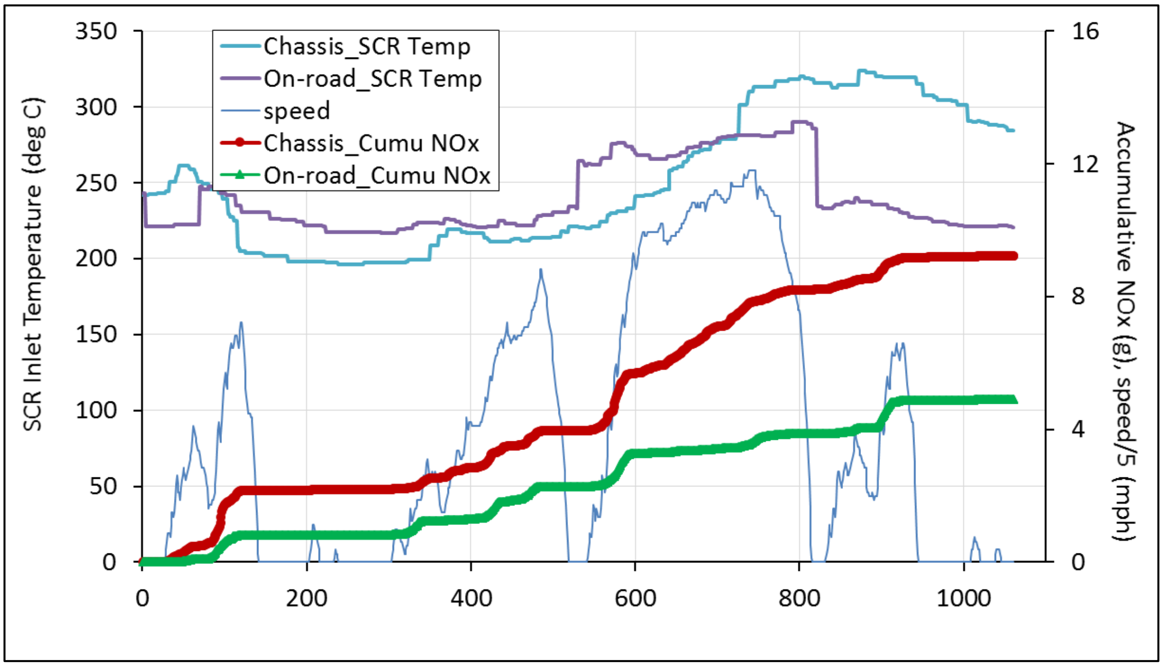


Figure 4-25 Comparison of engine out and SCR out NOx emission on a PPM basis from ECM for the chassis dynamometer and on-road UDDS tests for the Manufacturer A truck



Note that the on-road UDDS was not a continuous test. Three segments of on-road testing were not in the same order as in the chassis UDDS.

Figure 4-26 Comparison of SCR inlet temperature and accumulative Tailpipe NOx for the chassis dynamometer and on-road UDDS tests for the Manufacturer B truck

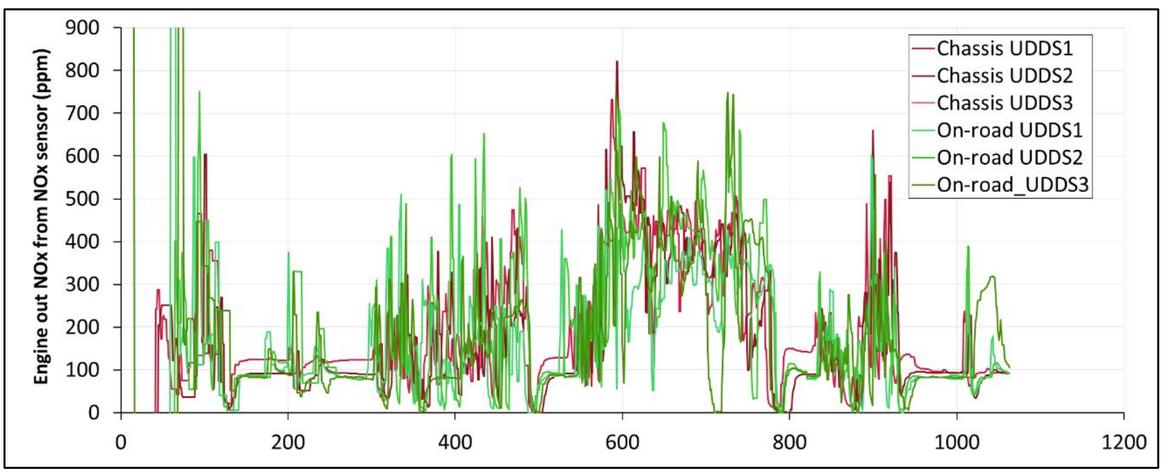


Figure 4-27 Comparison of engine out and SCR out NOx emission on a PPM basis from ECM for the chassis dynamometer and on-road UDDS tests for the Manufacturer B truck

4.1.3 Cruise NOx emission differences between chassis and engine dynamometer

NOx emissions for the Cruise cycles showed smaller differences than those found for the UDDS cycles, but nevertheless showed some interesting trends. Fuel injection timing and engine-out NOx are shown for the engine and chassis dynamometer cycles in Figure 4-28 for the Manufacturer A truck. This figure shows that the fuel timing for the chassis dynamometer testing is consistently advanced. The engine dynamometer timing showed different trends, however, with the timing being retarded for the initial approximately 1000 seconds before changing to advanced timing. The impacts on the engine out NOx emissions can be seen with the increases that start at the same time that the fuel injection timing becomes advanced.

For the engine dynamometer testing, engine-out NOx emissions were also evaluated as a function of engine load, as shown in Figure 4-29 and Figure 4-30 for the Manufacturer A and Manufacturer B trucks, respectively. The results show an interesting trend for the Manufacturer A engine, with the engine-out NOx emissions showing an upward trend with increasing load for the advanced timing test points for the engine dynamometer testing, while being relatively flat for the points where the engine has retarded timing on the engine dynamometer and for the chassis dynamometer testing. The Manufacturer B data are separated into two segments based on the first and the second 1,000 seconds of the cycle, which is roughly the time period where the Manufacturer A engine showed the differences in the fuel injection timing. The Manufacturer B engine showed much flatter trends in engine-out NOx emissions as a function of load. The Manufacturer B engine also showed similar trends in engine-out NOx emissions as a function of load for the engine out concentrations near 100 ppm. Note that the two 1000 second segments used to separate the data for the Manufacturer B engine correspond to the timeframe when the timing change was seen for the Manufacturer A engine.

Overall, the SCR out NOx emissions measured by PEMS over the Cruise cycle were low for the Manufacturer A engine. There was no significant difference in NOx between the different fuel injection timings for the Manufacturer A engine. The Manufacturer B engine had relatively higher SCR out NOx emissions compared to the Manufacturer A engine. The first 1000 secs for the Manufacturer B, where the loads were relatively higher, showed higher SCR out NOx emissions compared to those for second 1000 secs, indicating that the SCR may have less efficient for the first 1000 secs.

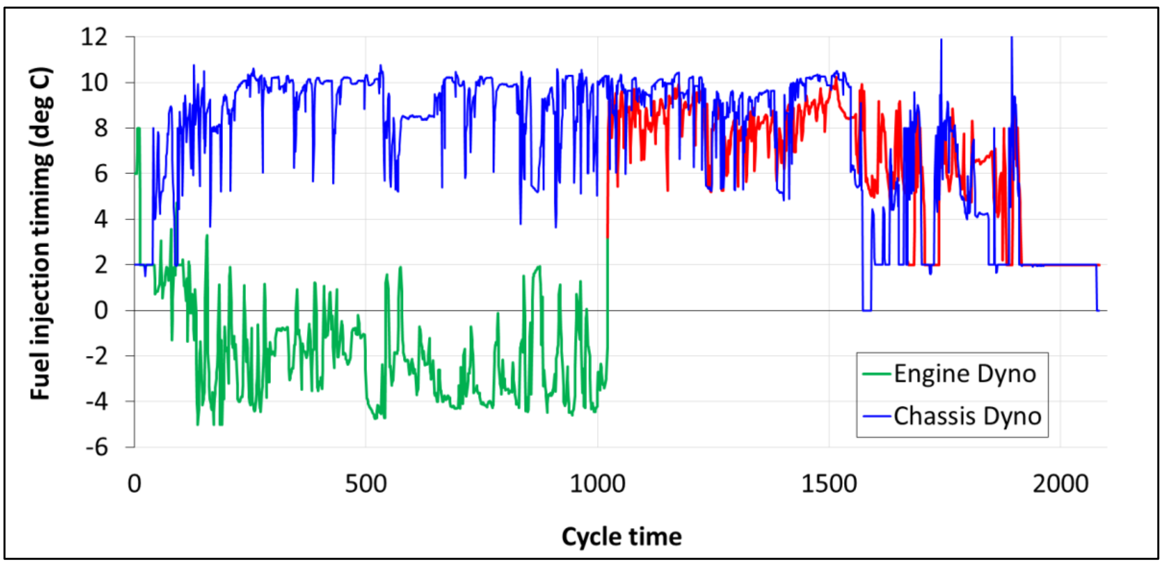


Figure 4-28 Fuel timing and engine out NOx of cruise cycles for engine dynamometer and chassis dynamometer for Manufacturer A

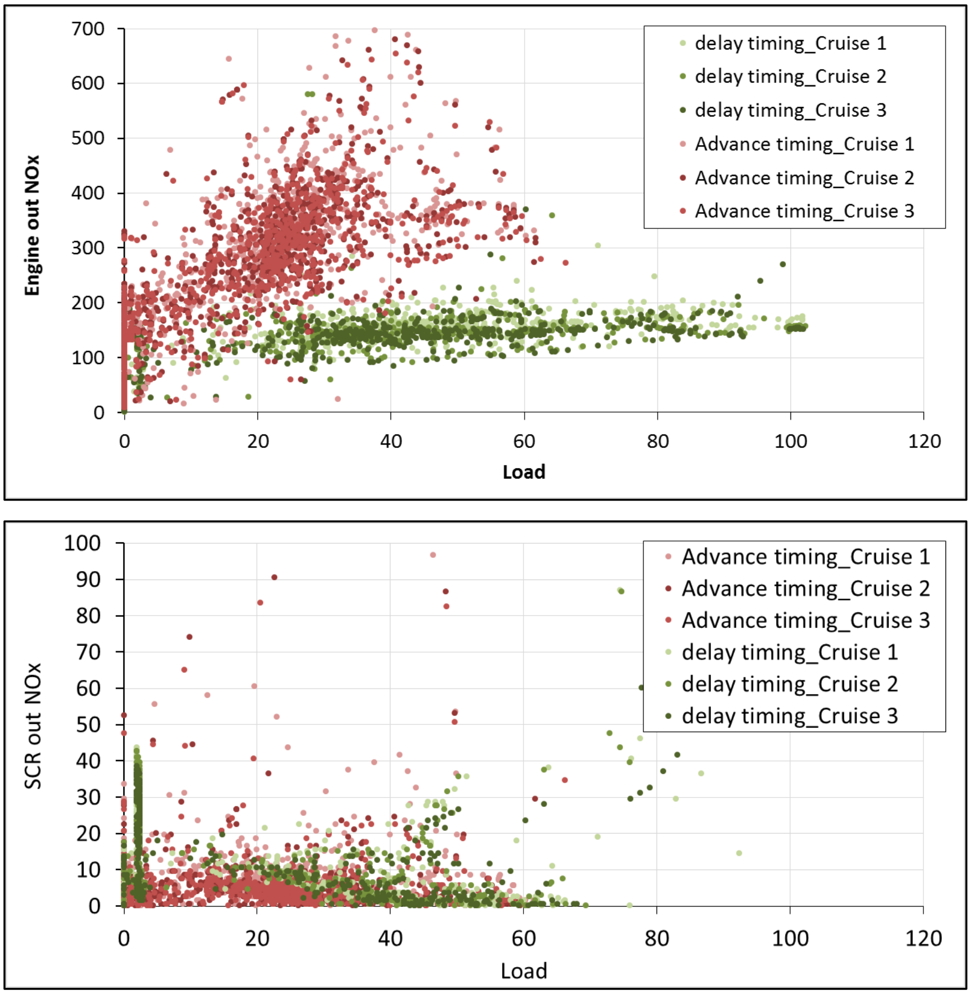


Figure 4-29 Engine out NOx and SCR out NOx as a function of load and fuel timing over the engine dynamometer testing for Manufacturer A

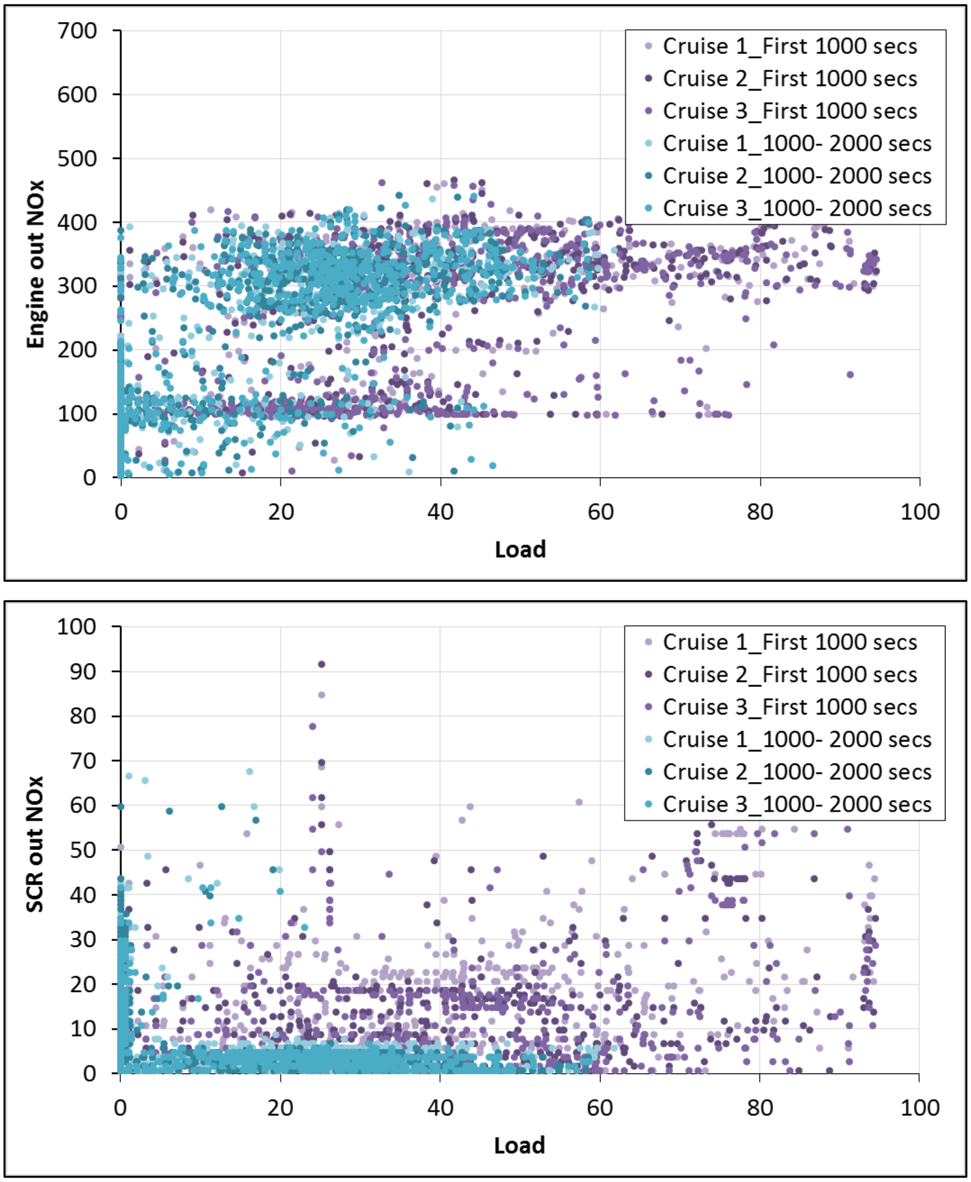


Figure 4-30 Engine out NOx and SCR out NOx as a function of load for the engine dynamometer for Manufacturer B

4.1.4 SCR efficiency

4.1.4.1 Average SCR efficiency by Test Cycle

Another important consideration in understanding NOx emissions is the SCR efficiency over the course of a test cycle. SCR efficiency was calculated based on the differences between engine-out and tailpipe NOx. In conjunction with this analysis, some comparisons between the sensor and PEMS NOx tailpipe values were made. Figure 4-31 provides a comparison of NOx emissions between SCR out NOx sensor and PEMS measurements in order to add confidence in the measurement from NOx sensor for both vehicles. For the Manufacturer A truck, the SCR NOx sensor had a good correlation to the PEMS with the slope of 1.06 and R^2 of 0.89, indicating the Manufacturer A NOx sensor measurement was comparable to the PEMS. For the Manufacturer B truck, the SCR NOx sensor didn't perform as well, with data being more scattered around the parity line. This could be due to the frequency of Manufacturer B NOx sensor being around 0.3

Hz. The slope of the correlations between the Manufacturer B SCR out NOx sensor and tailpipe PEMS NOx was 1 with an R^2 of 0.72.

Figure 4-32 shows the SCR efficiency for all the test cycles of both vehicles, based on the readings from engine out NOx sensor and tailpipe PEMS measurements. It should be noted that the SCR efficiency values in Figure 4-32 did not represent values over the whole cycles, as valid data from the engine out NOx sensor at the beginning of each cycle was not available due to the temperature threshold of 190˚C for the Manufacturer A truck and 250˚C for the Manufacturer B truck.

For the Manufacturer A truck, SCR efficiencies ranged from 68 to 98% for all the test cycles, with the SCR efficiencies for the cruise and hi-speed cruise cycles being higher than those for the urban driving cycles. The cold start cycles had relatively higher SCR efficiencies compared to the hot start cycles because the engine out NOx sensor only provided values for the last portion of the cold start cycle. For the urban driving cycles, the SCR efficiencies for the UDDS on the engine dynamometer were found to be higher than those for the chassis dynamometer and on-road tests, while the transient cycle showed the opposite trend. For the freeway driving and SET cycles, the SCR efficiencies were higher than 90% for all the cycles. In terms of on-road routes, the SCR efficiency of on-road routes were comparable to the freeway driving cycles. The Hesperia to Indio route had the lowest SCR efficiency of the three routes, which was consistent with the higher NOx emission rates found over this route.

For the Manufacturer B truck, SCR efficiencies ranged from 69 to 94% for all the test cycles, with the SCR efficiencies for the cruise and hi-speed cruise cycles being comparable with the urban driving cycles. The cold start cycles had relatively higher SCR efficiencies compared to the hot start cycles because the engine out NOx sensor only provided values for the last portion of the cold start cycle. For the urban driving cycles, the SCR efficiencies for the UDDS cycle on the engine dynamometer and the on-road tests were found to be slightly higher than those from the chassis dynamometer, while the transient cycle showed the opposite trend. For the freeway driving and SET cycles, the SCR efficiency ranged from 83 to 94%, which was lower than the values for Manufacturer A. In terms of on-road routes, the SCR efficiency of on-road routes were comparable to the freeway driving cycles. The Riverside to Hesperia to Indio route with the highest load had the lowest SCR efficiency of the three routes.

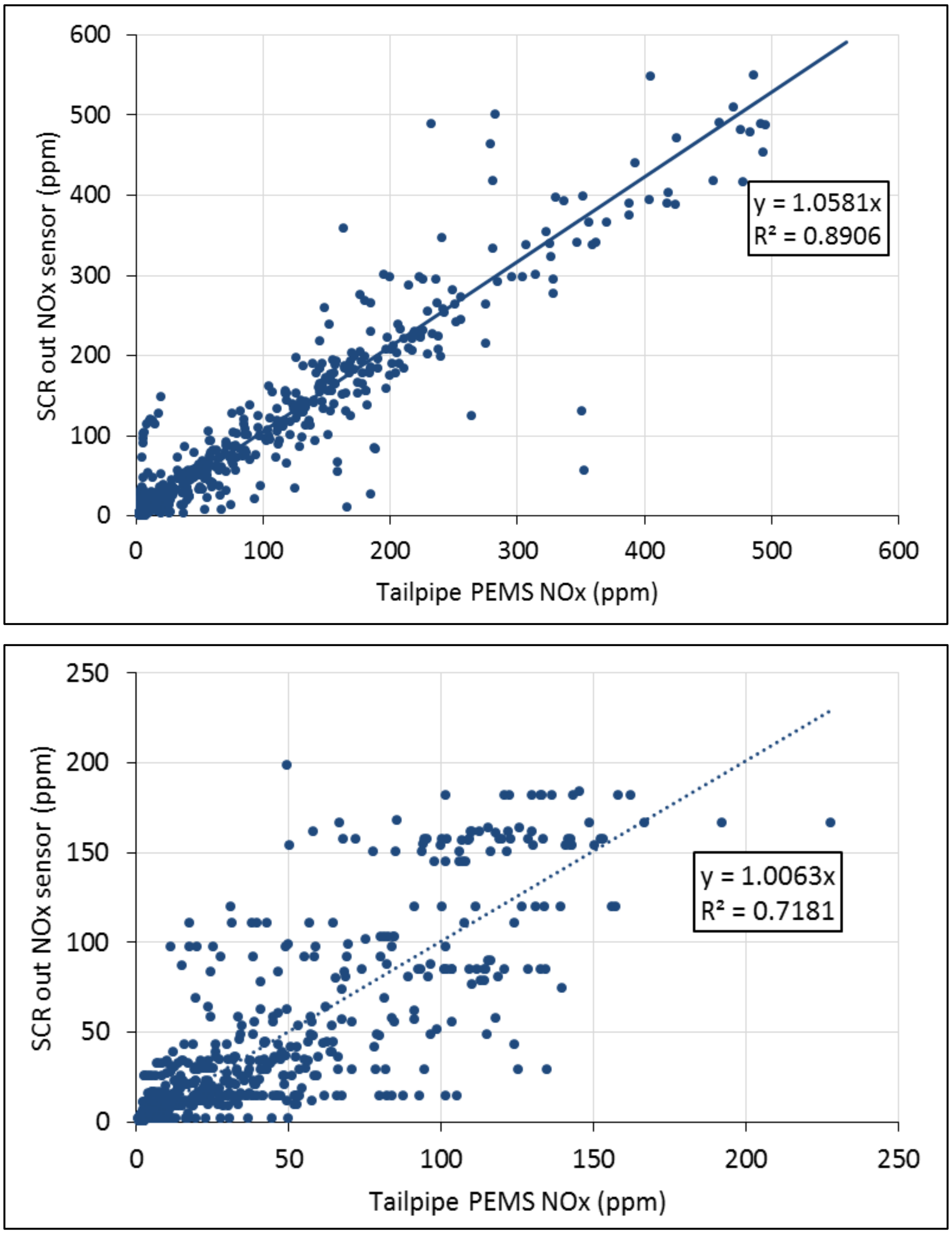
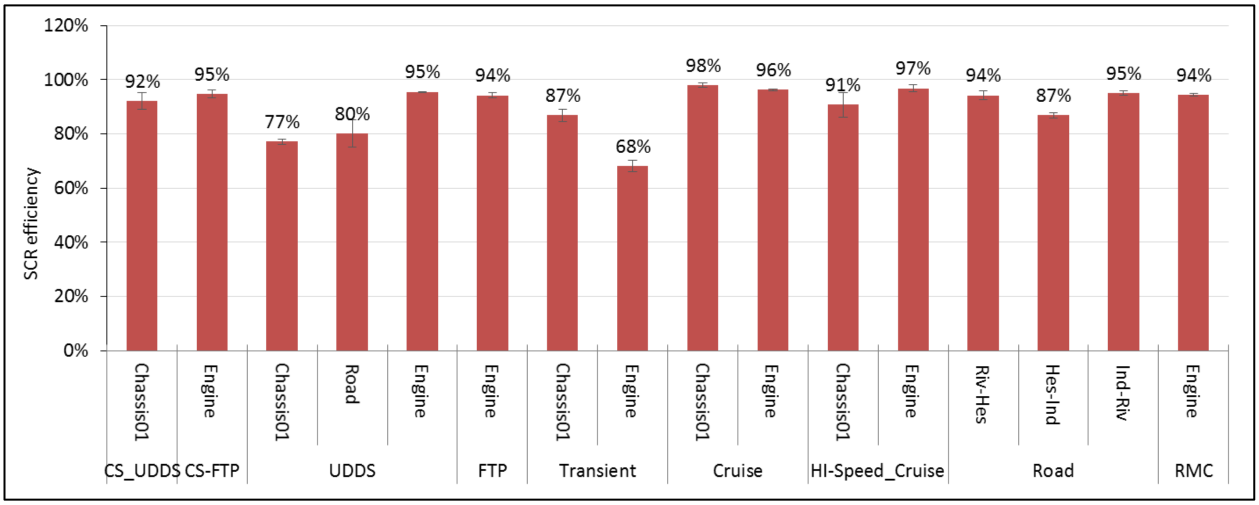
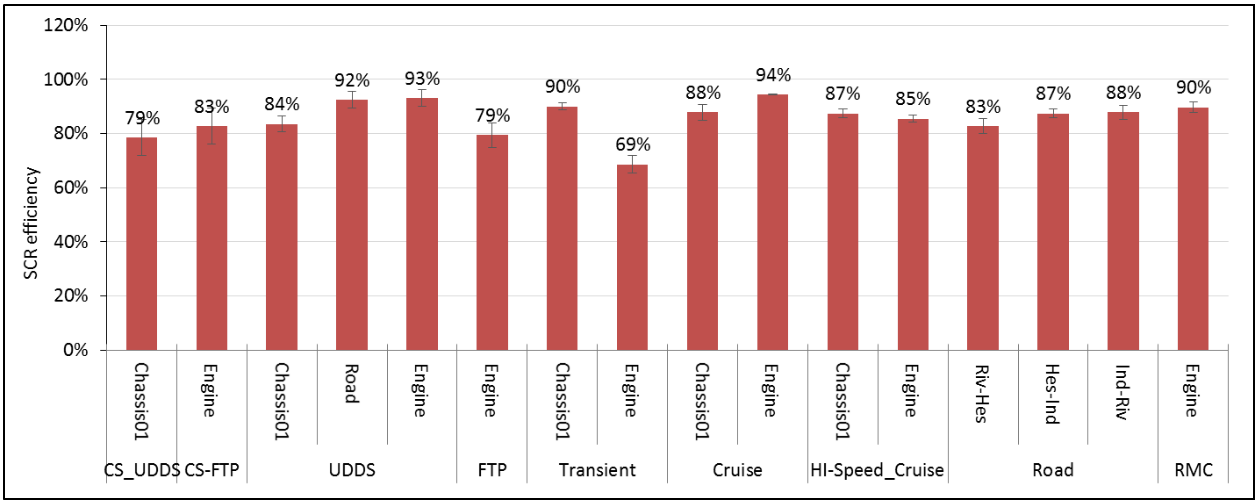


Figure 4-31 SCR out sensor vs tailpipe PEMS for Manufacturer A (Top) and Manufacturer B (Bottom)



Note that the SCR efficiency was calculated based on engine out NOx sensor and PEMS measurement. The portions of cycle that engine out NOx sensor didn't work were excluded from calculation.



Note that the SCR efficiency was calculated based on engine out NOx sensor and PEMS measurement. The portions of cycle that engine out NOx sensor didn't work were excluded from calculation.

Figure 4-32 SCR efficiency for Manufacturer A (Top) and Manufacturer B (Bottom)

4.1.4.2 SCR efficiency as a function of SCR temperature

Figure 4-33 and Figure 4-34 show SCR efficiency for the chassis dynamometer, on-road and engine dynamometer testing as a function of SCR temperature for the Manufacturer A and Manufacturer B trucks, respectively. All the test data of each test was divided into three groups based on SCR inlet temperatures: SCR inlet temperatures< 200˚C, 200˚C< =SCR inlet temperatures<250˚C and SCR inlet temperatures>=250˚C. The SCR efficiencies for each group were calculated based the integrated engine out NOx mass from the engine out NOx sensors and the integrated tailpipe NOx mass from PEMS. The SCR inlet temperatures were the average values of each group. The SCR efficiency values did not represent the values over the whole cycles, as valid data from the engine out NOx sensor at the beginning of each cycle was not available due to the temperature threshold of 190˚C.

For the Manufacturer A truck, the overall SCR efficiency was above 80% for all the test conditions when the SCR inlet temperatures were above 250˚C and remained constant as the temperature increased. In terms of different test conditions, the engine dynamometer showed the highest SCR efficiency (>90%) with the SCR temperatures above 250˚C. The on-road testing had comparable SCR efficiency values to those of the engine dynamometer with SCR temperatures above 250˚C and the chassis dynamometer testing had the lowest SCR efficiency, which is consistent with the observation of lowest SCR inlet temperatures. When the SCR temperatures were below 250˚C, the SCR efficiency dropped, especially for the chassis dynamometer and on-road testing. The lowest SCR efficiency was around 40% for both the chassis and on-road testing, under conditions where the SCR temperature was lower than 200˚C.

For the Manufacturer B truck, the overall SCR efficiency was above 80% for most of the test conditions when the SCR inlet temperatures were above 250˚C, with a slight drop as the temperature increased from 250 to 350˚C. In terms of different test conditions, there is no significant difference in SCR efficiency between different test conditions when the SCR temperatures were above 250˚C. When the SCR temperatures were below 250˚C, the SCR efficiency dropped and showed a wider range, especially for the engine dynamometer and on-road testing. The lowest SCR efficiencies were around 50% to 60% for all the test conditions with the SCR temperature lower than 200˚C.

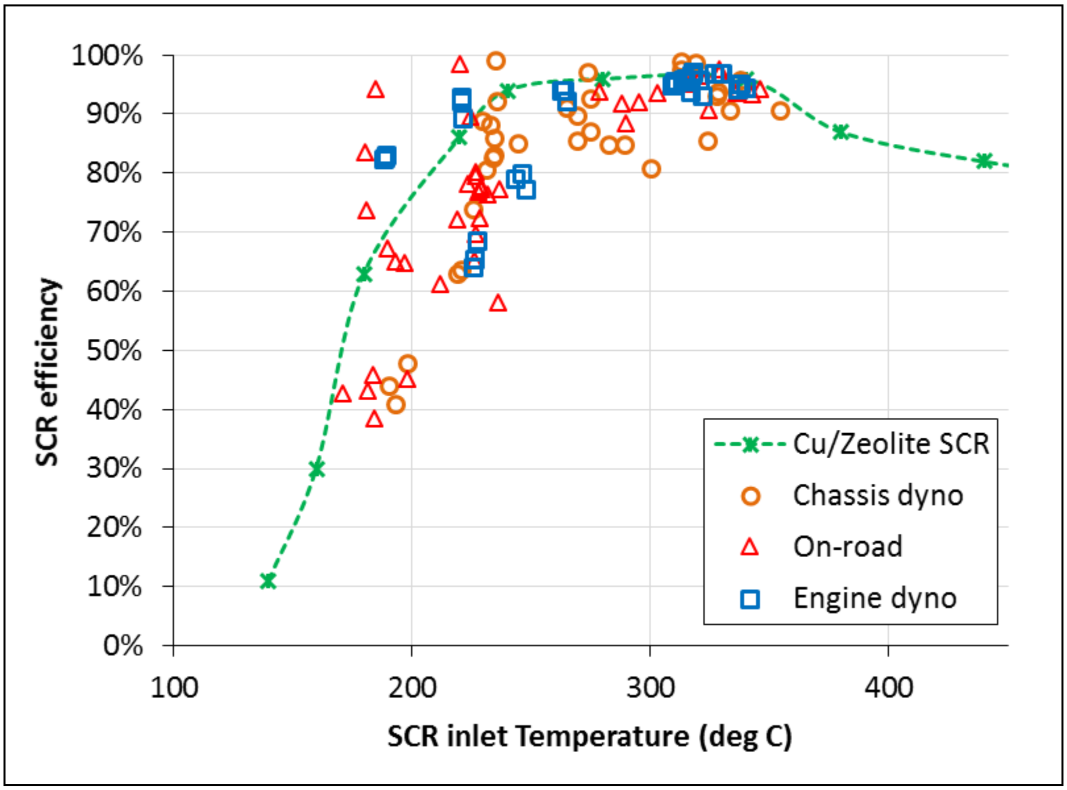


Figure 4-33 SCR efficiency as a function of SCR temperature for Manufacturer A and NOx conversion efficiency of different SCR catalysts (Cavataio et al., 2007)

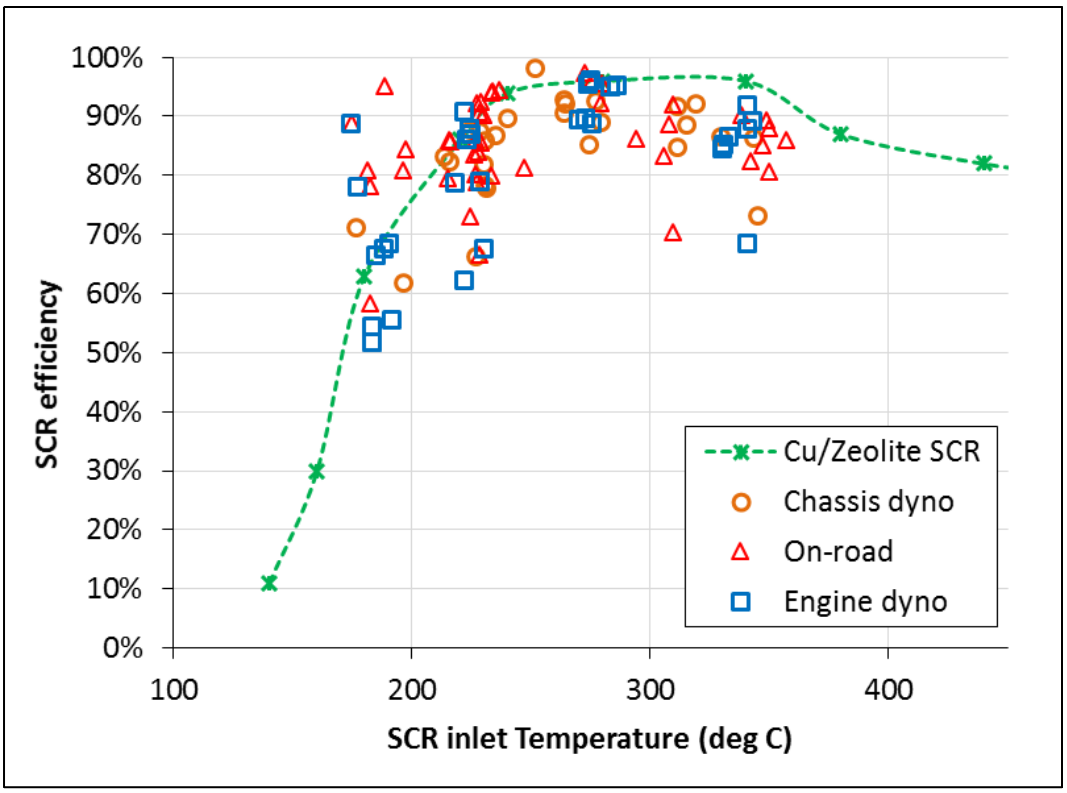


Figure 4-34 SCR efficiency as a function of SCR temperature for Manufacturer B and NOx conversion efficiency of different SCR catalysts (Cavataio et al., 2007)

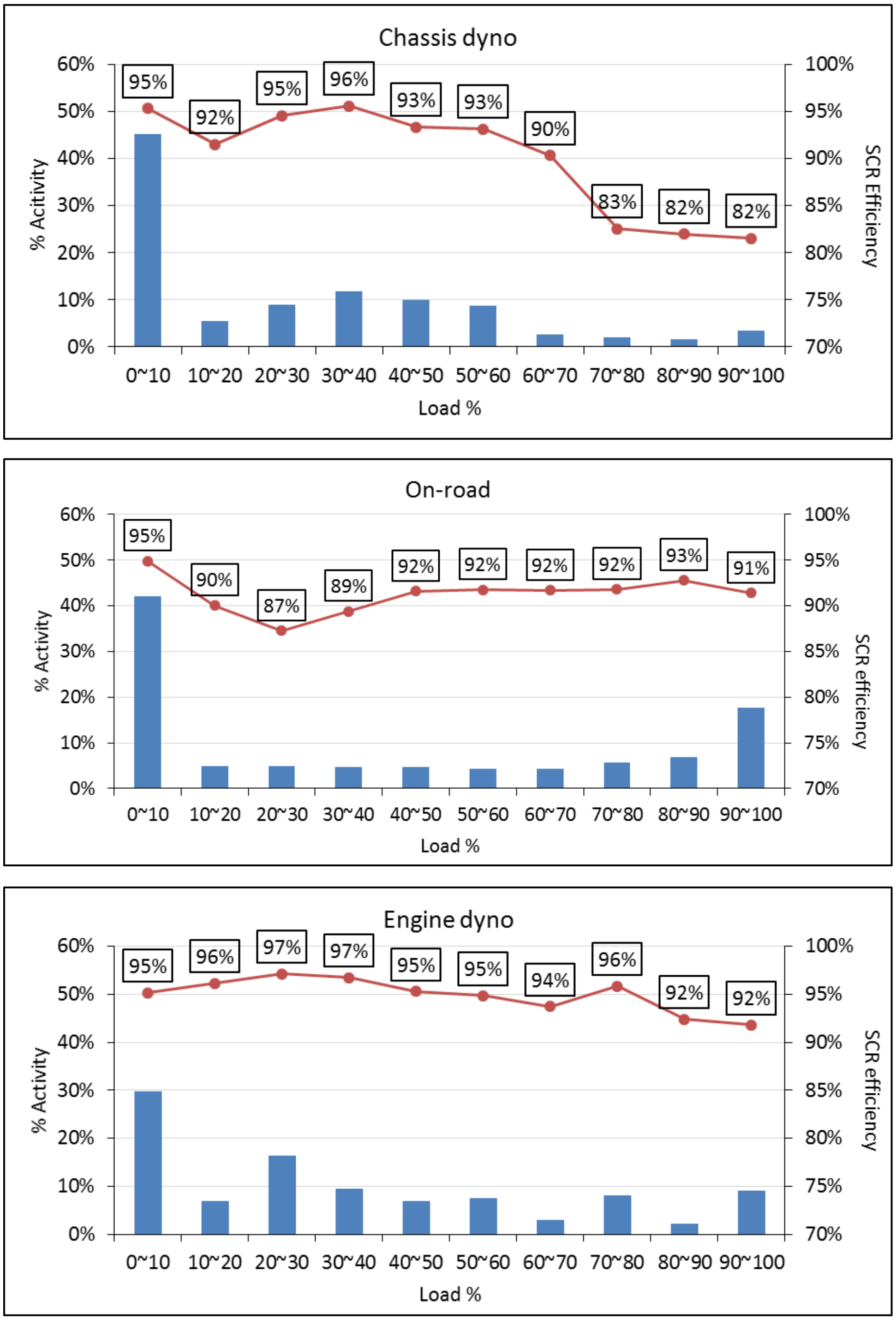
The SCR conversion efficiency in this study can also be compared that to experimental values (Cavataio et al., 2007), as both vehicles were equipped with Cu/Zeolite based SCR. Their experimental data showed that SCR efficiencies were above 90% when the SCR inlet temperatures were higher than 250°C, which was higher than the values seen in the present study for both vehicles, except for the engine dynamometer testing for the Manufacturer A truck. The SCR efficiency started to drop as the SCR inlet temperatures went above 350°C for the experimental data, which was consistent with the results for the Manufacturer B truck. The experimental data also showed that SCR efficiency was temperature dependent for SCR inlet temperatures below 200°C, which is consistent with the results for both vehicles.

4.1.4.3 SCR efficiency as a function of load

Figure 4-35 and Figure 4-36 show SCR efficiencies for chassis dynamometer, on-road and engine dynamometer testing as a function of load for the Manufacturer A and Manufacturer B trucks, respectively. The test data was divided into ten groups based on load. The SCR efficiency for each group was calculated based the integrated engine out NOx mass from engine out NOx sensors and the integrated tailpipe NOx mass from PEMS. The SCR efficiency values did not represent the values over the whole cycles, as valid data from the engine out NOx sensor at the beginning of each cycle was not available due to the temperature threshold.

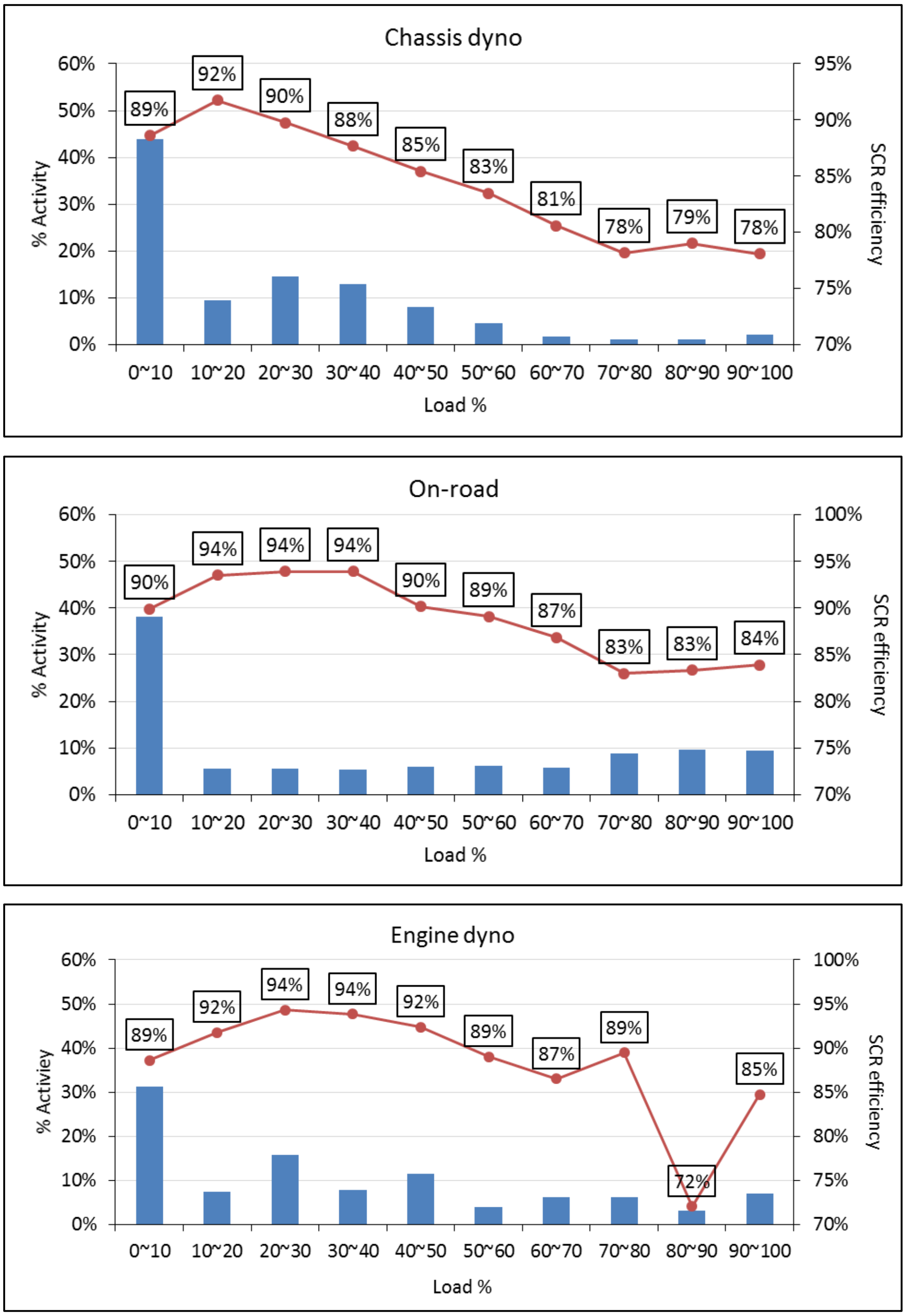
For the Manufacturer A truck, the overall SCR efficiency was above 80% for all the load points. The highest SCR efficiency was observed between 30 to 60% load with the efficiency higher than 90%, except for the 30 to 40% load of on-road testing. The lowest SCR efficiencies were found between 10-30% load for the chassis dynamometer and on-road testing due to the lower SCR temperatures at these lower loads, although this trend was not found for the engine dynamometer testing. The SCR efficiency also dropped at the high load operations for the chassis and engine dynamometer testing, but not for on-road testing. This was because the chassis and engine dynamometer testing had higher fractions of transient operations than the on-road testing. Also, high load operations for chassis and engine dynamometer typically occurred during accelerations, while the high load operations for the on-road testing were typically under cruise conditions.

For the Manufacturer B truck, the overall SCR efficiency was above 70% for all the load points. The highest SCR efficiency was observed between 10 to 40% load, with the efficiencies higher than 90%, except for 30 to 40% load of chassis testing. The SCR efficiency did not drop in the 10-30% load range, as might be expected for lower load operation with lower SCR temperatures. However, the SCR efficiency dropped as the load increased in the middle load range, and the SCR efficiency remained lower under high load conditions for all the test conditions, even for the on-road testing where most of the high load operation was under cruise conditions. This was consistent with the lower NTE pass rate for the Manufacturer B truck, as the NTE was designed to capture activity during the high load operations.



Note that engine dynamometer had extra cycles compared with Chassis dynamometer.

Figure 4-35 SCR efficiency as a function of load for Manufacturer A



Note that engine dynamometer had extra cycles compared with Chassis dynamometer.

Figure 4-36 SCR efficiency as a function of load for Manufacturer B

4.1.4.4 Real-time SCR efficiency

Plots of real-time SCR efficiency over the UDDS chassis and engine dynamometer cycles are provided in Figure 4-37 and Figure 4-38 for the Manufacturer A truck and Figure 4-39 and Figure 4-40 for the Manufacturer B truck, along with the corresponding SCR inlet temperatures. The real-time SCR efficiency for the chassis dynamometer cycles had a wide range, with values from 20 to near 100% for Manufacturer A and 40 to 100% for Manufacturer B. Some low real-time SCR efficiencies were observed for both vehicles when the SCR temperatures were above 250˚C. Lower SCR efficiencies were also observed during lower load operation when the engine out NOx emissions were not very high. The real-time SCR efficiencies fluctuated less and remained >90% for most of UDDS cycle on engine dynamometer testing.

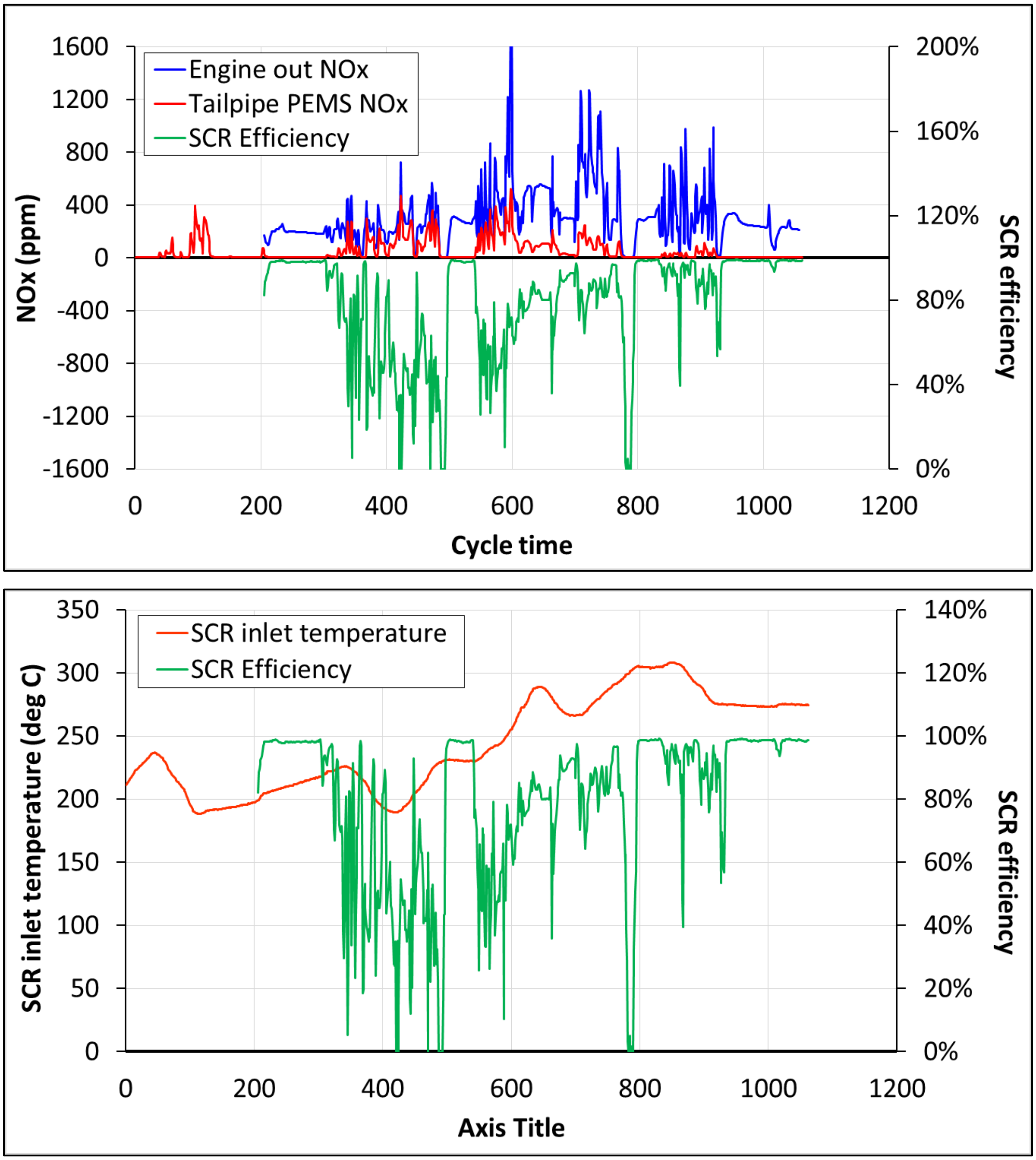


Figure 4-37 Real-time SCR efficiency for UDDS chassis dynamometer cycle for Manufacturer A

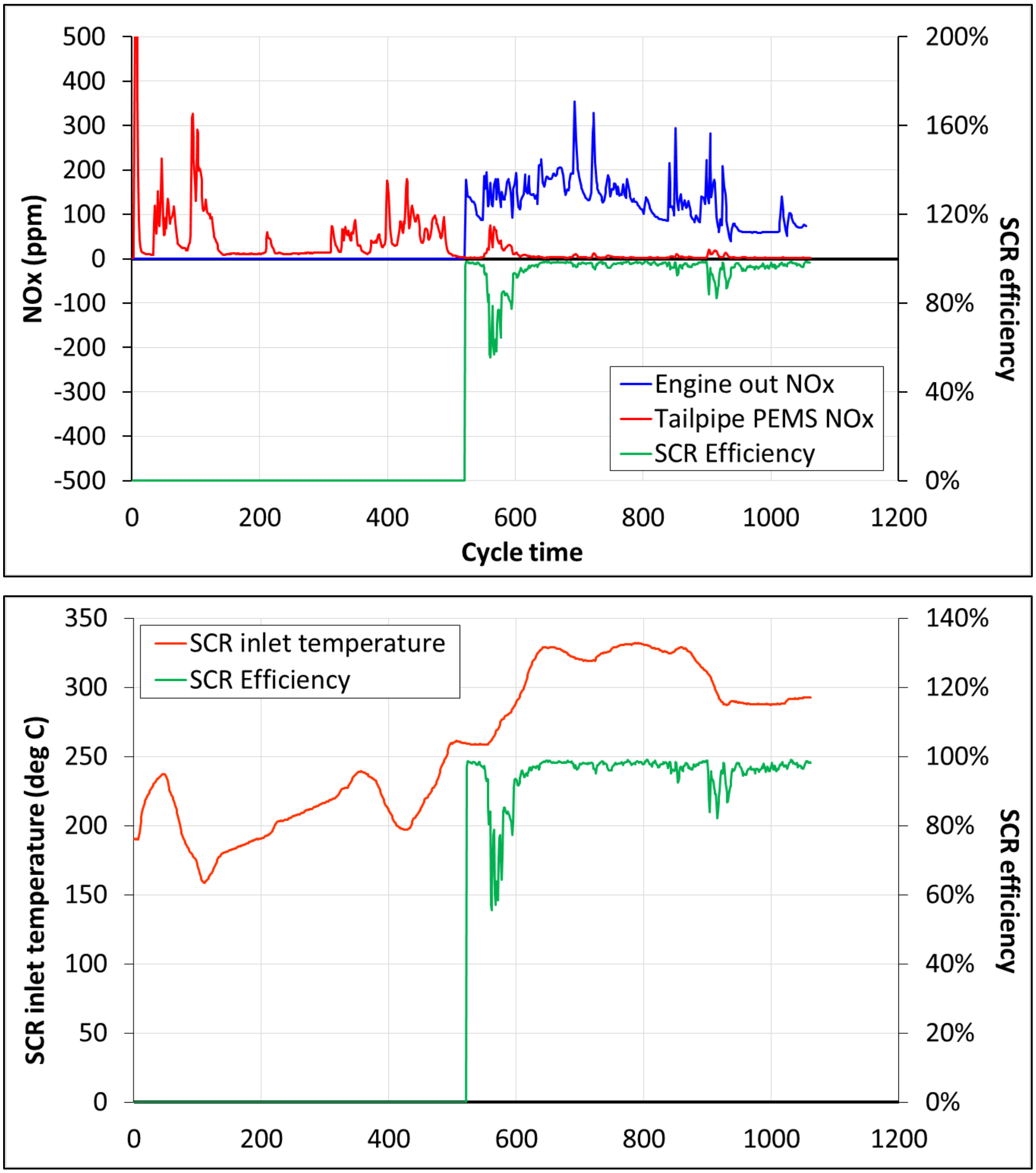


Figure 4-38 Real-time SCR efficiency for UDDS engine dynamometer cycle for Manufacturer A

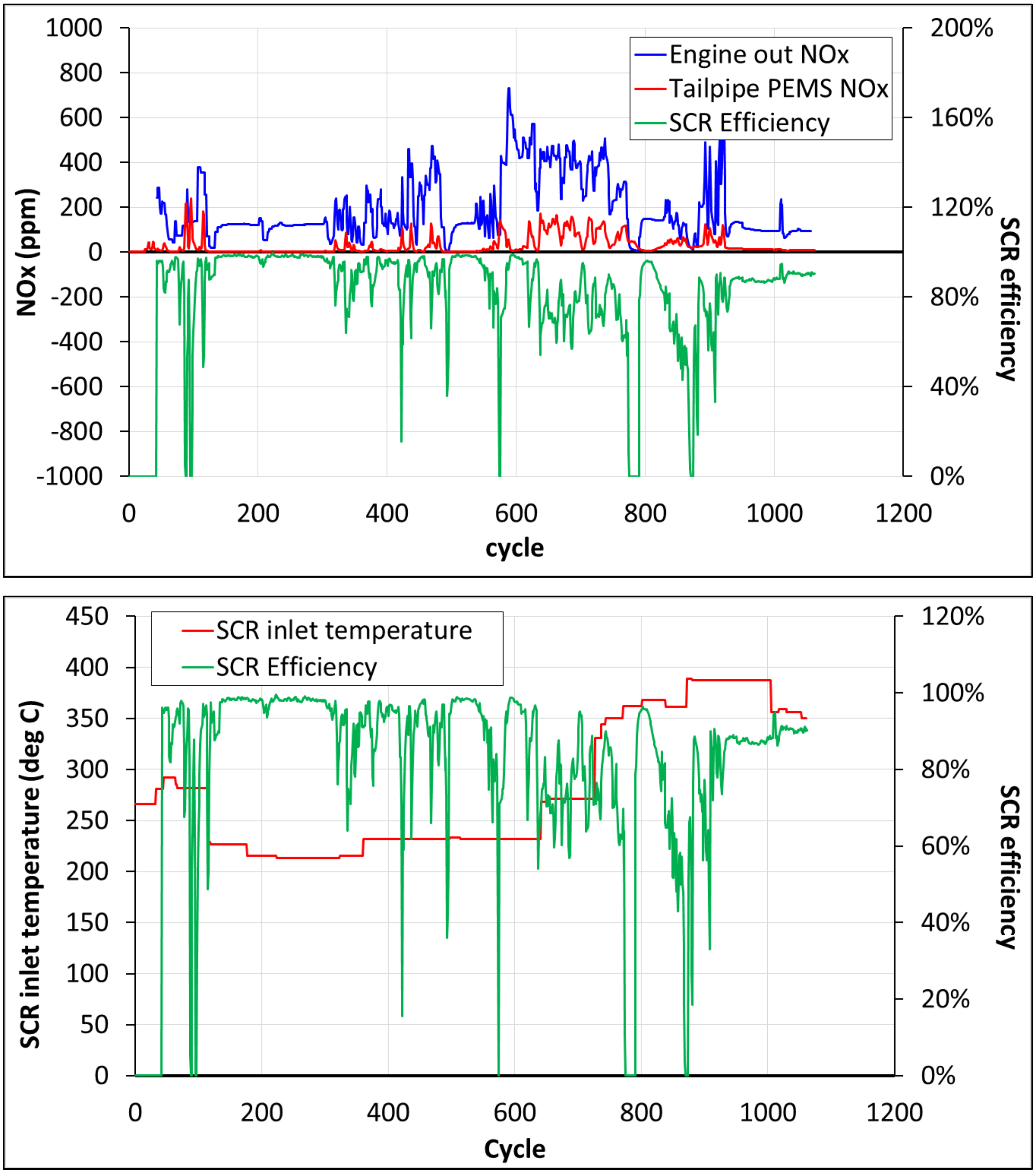


Figure 4-39 Real-time SCR efficiency for UDDS chassis dynamometer cycle for Manufacturer B

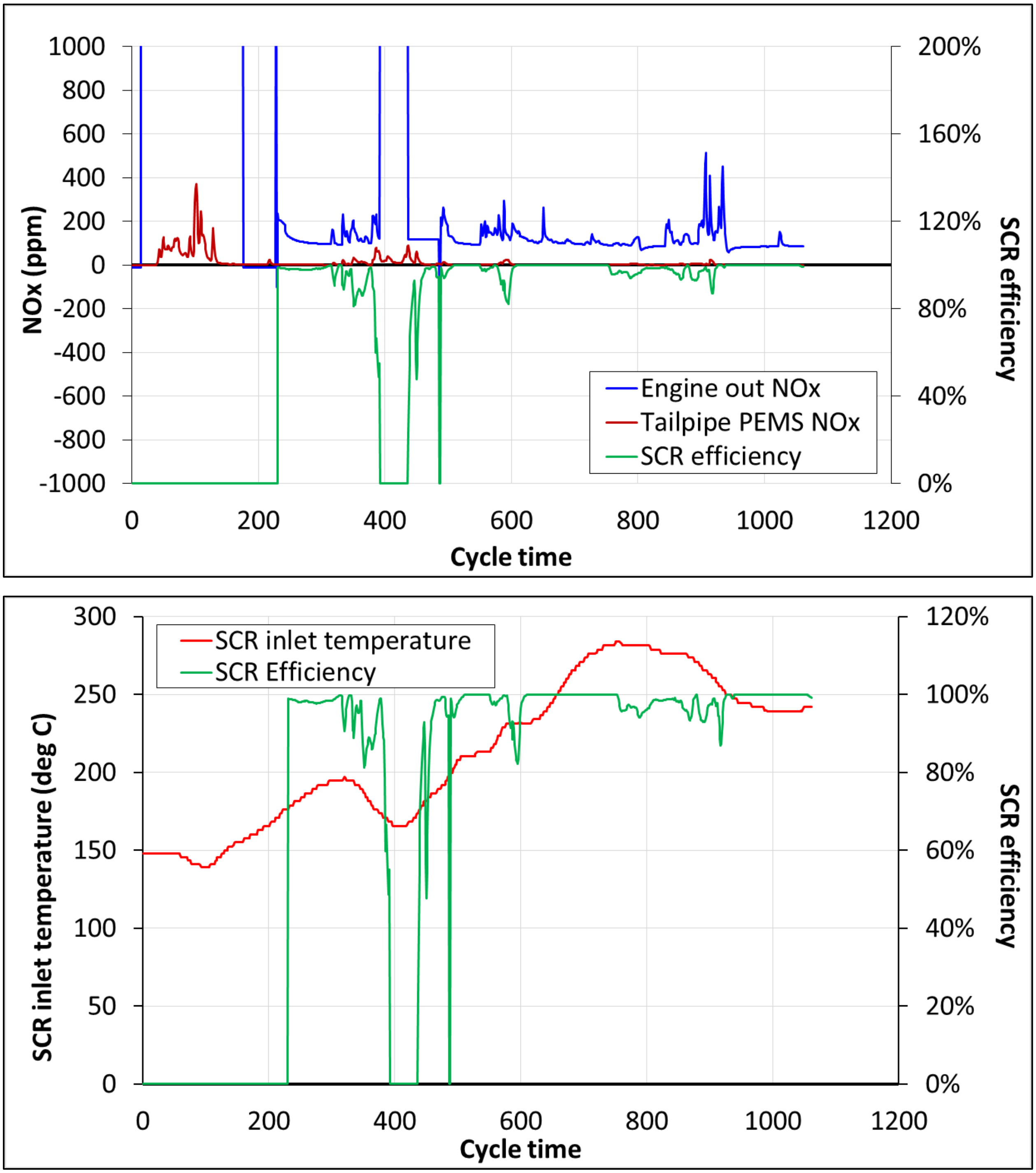


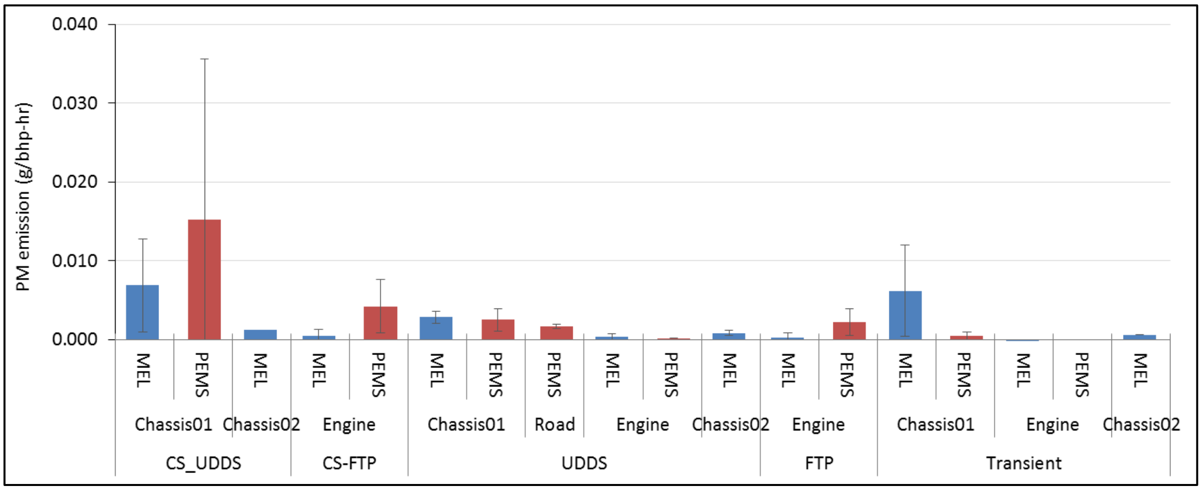
Figure 4-40 Real-time SCR efficiency for UDDS engine dynamometer cycle for Manufacturer B

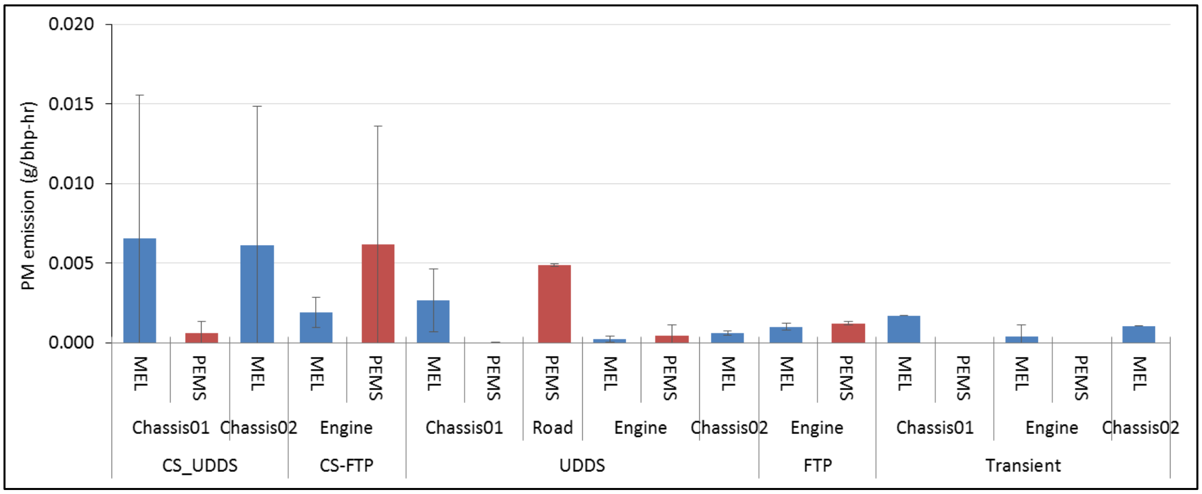
4.2 PM Emissions

PM emissions for the Manufacturer A and Manufacturer B trucks are shown on a g/bhp-hr and a g/mi basis, respectively, in Figure 4-41 and Figure 4-42 and for the urban driving cycles, including the CS-UDDS, UDDS, CS-FTP, FTP and HHDDT-transient cycles. PM emissions for the Manufacturer A and Manufacturer B trucks are shown on a g/bhp-hr and a g/mi basis, respectively, in Figure 4-43 and Figure 4-44 for the freeway driving cycles, including the cruise and high-speed cruise cycles as well as the results from the on-road testing and RMC engine dynamometer testing.

PM mass emissions were very low for most of the test cycles. Average PM emissions were below 0.01 g/bhp-hr for both vehicles and all tests, with the exception of the cold start UDDS PEMS measurements and the hi-speed cruise first chassis dynamometer test for the Manufacturer A truck. The PM emissions for the Manufacturer A truck were on the order of 0.001 g/bhp-hr for most urban cycles, except for the cold start-UDDS, the UDDS, and Transient initial chassis dynamometer tests. The PM emissions for the Manufacturer B truck were on the order of 0.0025 g/bhp-hr or less for most cycles, except for the initial and final cold start-UDDS chassis dynamometer tests, and the PEMS measurements for the CS-FTP and on-road UDDS tests. The PM emissions for the hi-speed cruise cycle were much higher than the values of other freeway driving cycles for the Manufacturer A truck. The PM emissions for the Manufacturer B truck were all below 0.0035 g/bhp-hr for all the freeway driving cycles, and the results were comparable between different cycles. On a g/mi basis, average PM emissions were at or below 0.08 for both vehicles and all test cycles. For many cycles, average PM emissions were on the order of 0.01 g/mi or less.

The very low PM levels are consistent with the results of previous studies. For the previous CARB EMFAC2014 study, PM emission rates were below 0.015 g/mi for most vehicle/cycle combinations as well, although some hi-speed cruise points did show PM emission rates ranging from 0.028 to 0.055 g/mi (California Air Resources Board, 2015a, 2015b). These results were comparable with the low PM emission level of the hot start cycles of this study. Jiang et al. (2018) found PM emissions were below 0.015 g/mi and 0.006 g/bhp-hr for five 2010+ vehicles for most vehicle/cycle combinations, except for some hi-speed cruise cycle. In this study, the PM emission rates of the hi-speed cruise cycles were also found to be relatively higher than the values of others cruise cycles, especially for the Manufacturer A truck. In a study by Miller et al. (2013) of goods movement trucks, PM emissions were ≤0.002 g/mi for most vehicle/cycle combinations, although there were a few vehicle/cycle combinations above 0.002 g/mi for some of the 2010+ vehicles on the Regional and near-dock drayage cycles. Carder et al. (2014) found PM emissions of <0.010 g/mi for a 2010+ SCR-equipped truck over a range of cycles including a UDDS, and near-dock, local, and regional drayage cycles.





Note PM results of one UDDS cycle over engine dynamometer based on MEL measurement was eliminated from calculation due to the contamination of the filter.

Figure 4-41. Average PM Mass Emissions on a g/bhp-hr Basis for the urban cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

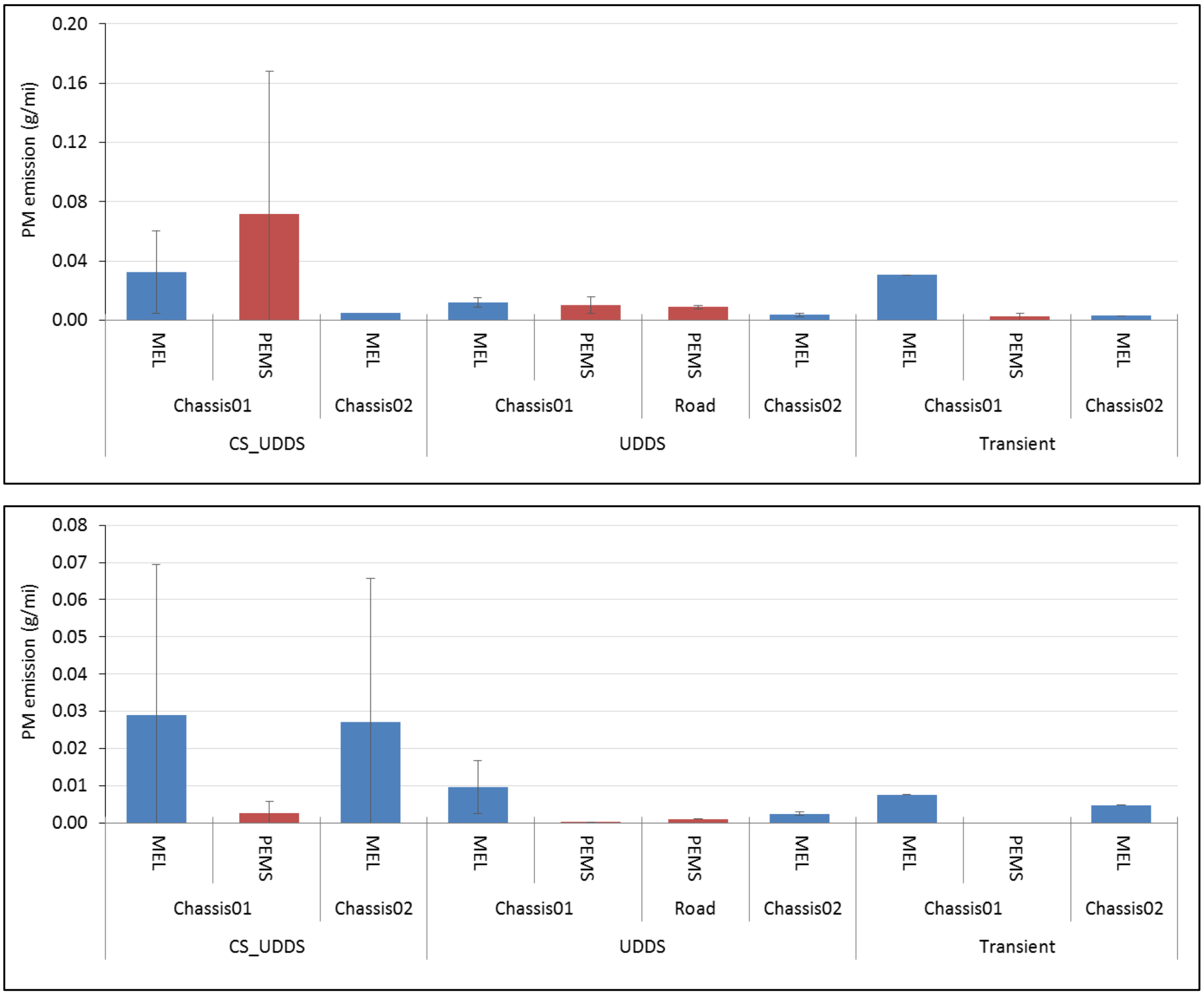
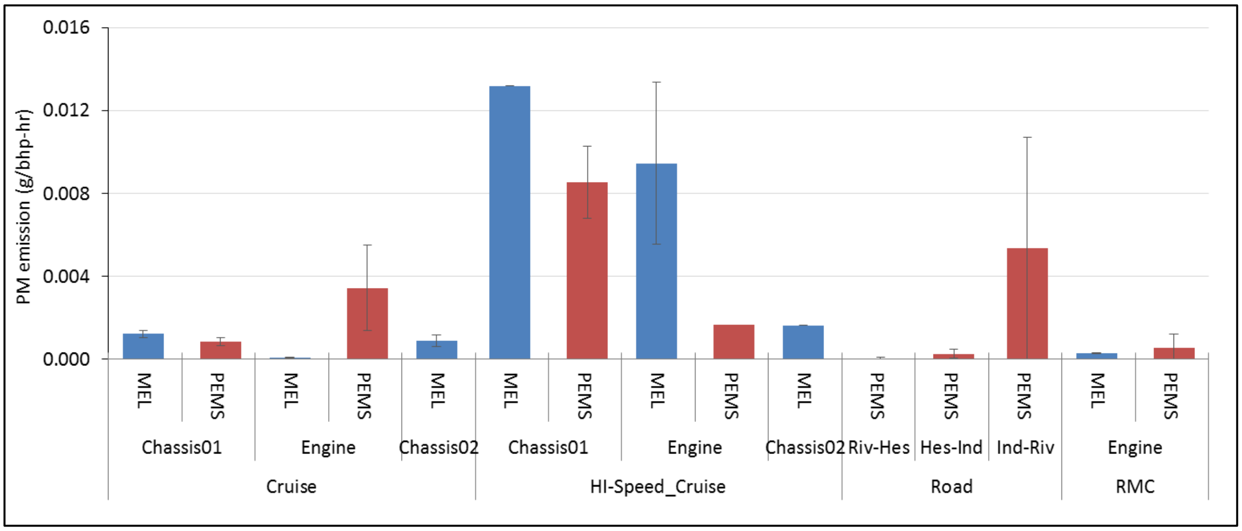


Figure 4-42. Average PM Mass Emissions on a g/mi Basis for the urban cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)



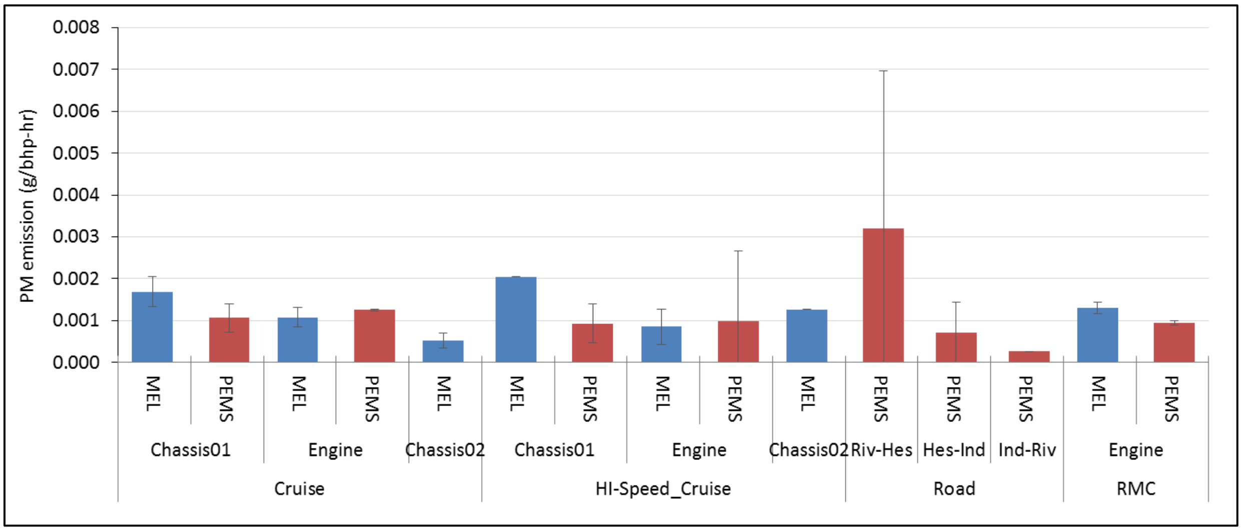


Figure 4-43 Average PM Mass Emissions on a g/bhp-hr Basis for the Freeway and SET cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

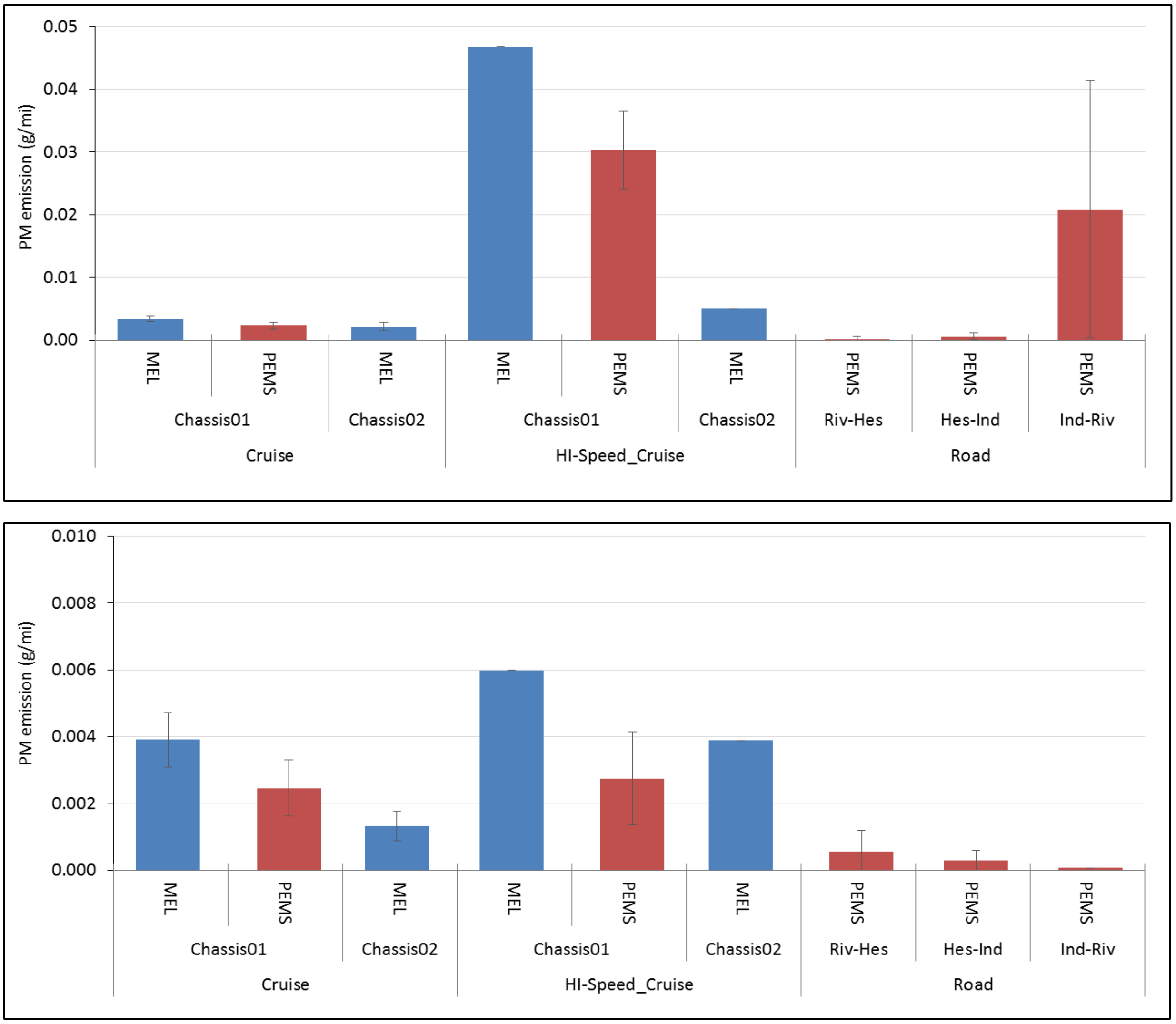


Figure 4-44 Average PM Mass Emissions on a g/mi Basis for the Freeway and SET cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

4.3 CO Emissions

CO emissions for the Manufacturer A and Manufacturer B trucks are shown on a g/bhp-hr and a g/mi basis, respectively, in Figure 4-45 and Figure 4-46 for the urban driving cycles, including the CS-UDDS, UDDS, CS-FTP, FTP and HHDDT-transient cycles. CO emissions for the Manufacturer A and Manufacturer B trucks are shown on a g/bhp-hr and a g/mi basis, respectively, in Figure 4-47 and Figure 4-48 for the freeway driving cycles, including the cruise and high-speed cruise cycles as well as the results from the on-road and RMC engine dynamometer testing.

CO emissions were higher for the urban test cycles than the cruise/highway conditions. The emissions for the urban cycles ranged from 0.002 to 1.76 g/bhp-hr depending on the test point. The highest emissions were seen for the cold start tests, including the CS_UDDS and CS_FTP. The lowest CO emissions were seen for the on-road UDDS and chassis dynamometer transient test. CO emissions for the highway cycles were all below 0.15 g/bhp/hr. Overall, the CO emission rates were considerably below the 15.5 g/bhp-hr standards for all test points. On a g/mi basis, CO emissions ranged from 1 to 5 g/mi for the urban cycles and were all below 0.6 g/mi for the highway cycles.

In comparison with other studies, Jiang et al. (2018) found CO emissions were below 0.2 g/mi for five low mileage 2010 and newer vehicles over multiple cycles, generally lower than the values observed in the present study. In a study by Miller et al. (2013), CO emission rates over the UDDS were 0.064 g/mi or below for most diesel trucks, with many of those levels being at or below the background level, and much lower than those of this study. Carder et al. (2014) found CO emissions of 0.216, 0.749, 0.169, and 0.854 g/mi for a 2010+ SCR-equipped truck over UDDS, and near-dock, local, and regional drayage cycles, respectively, which were comparable with the CO emission rates of hot start urban driving cycles of this study. A CARB (2015a, 2015b) study also showed CO emissions in a range from 1.64 to 4.75 g/mi for some vehicle/cycle points, in the range of some of the higher values in the present study.

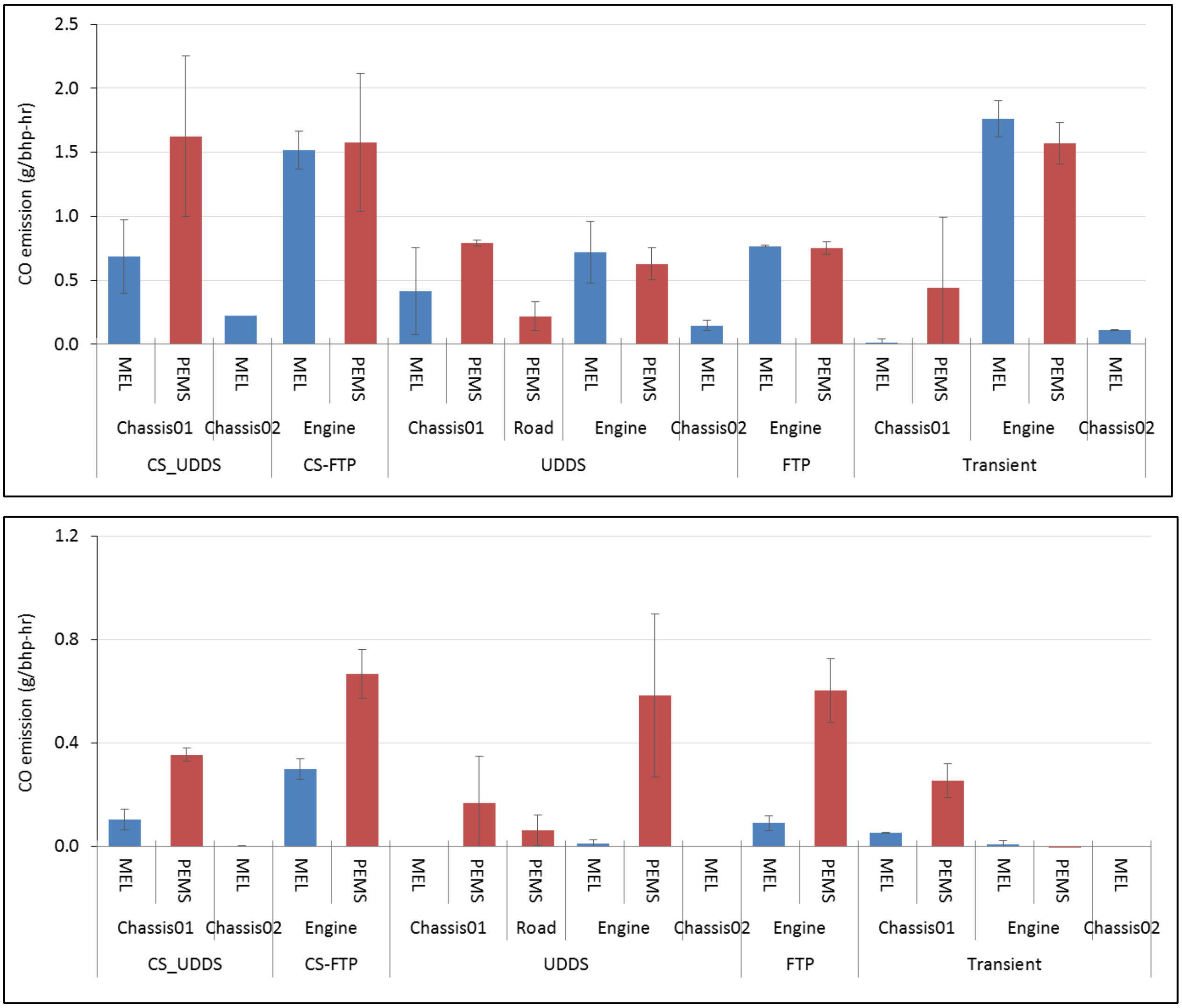


Figure 4-45. Average CO Emissions on a g/bhp-hr Basis for the urban cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

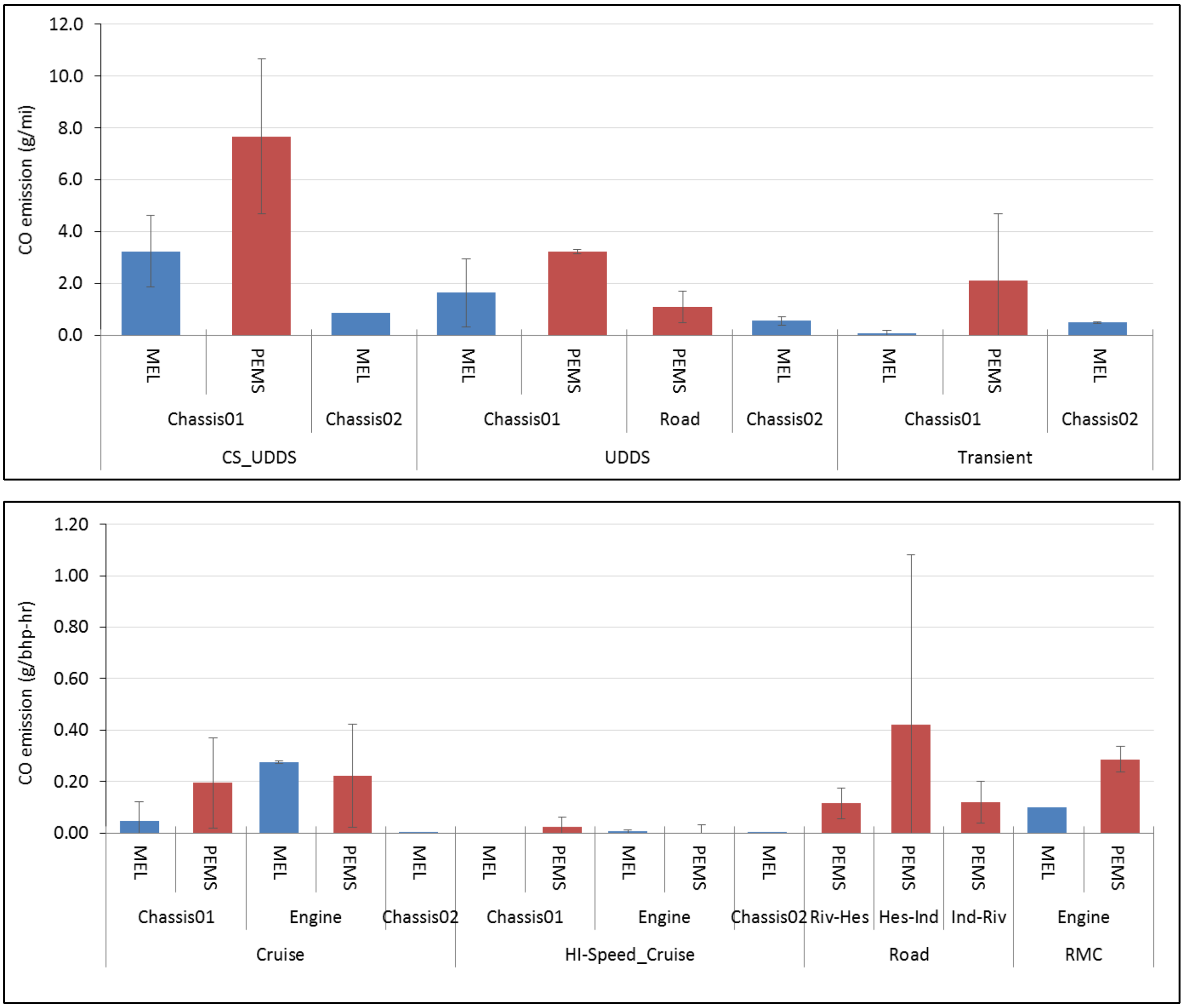


Figure 4-46 Average CO Emissions on a g/mi Basis for the urban cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

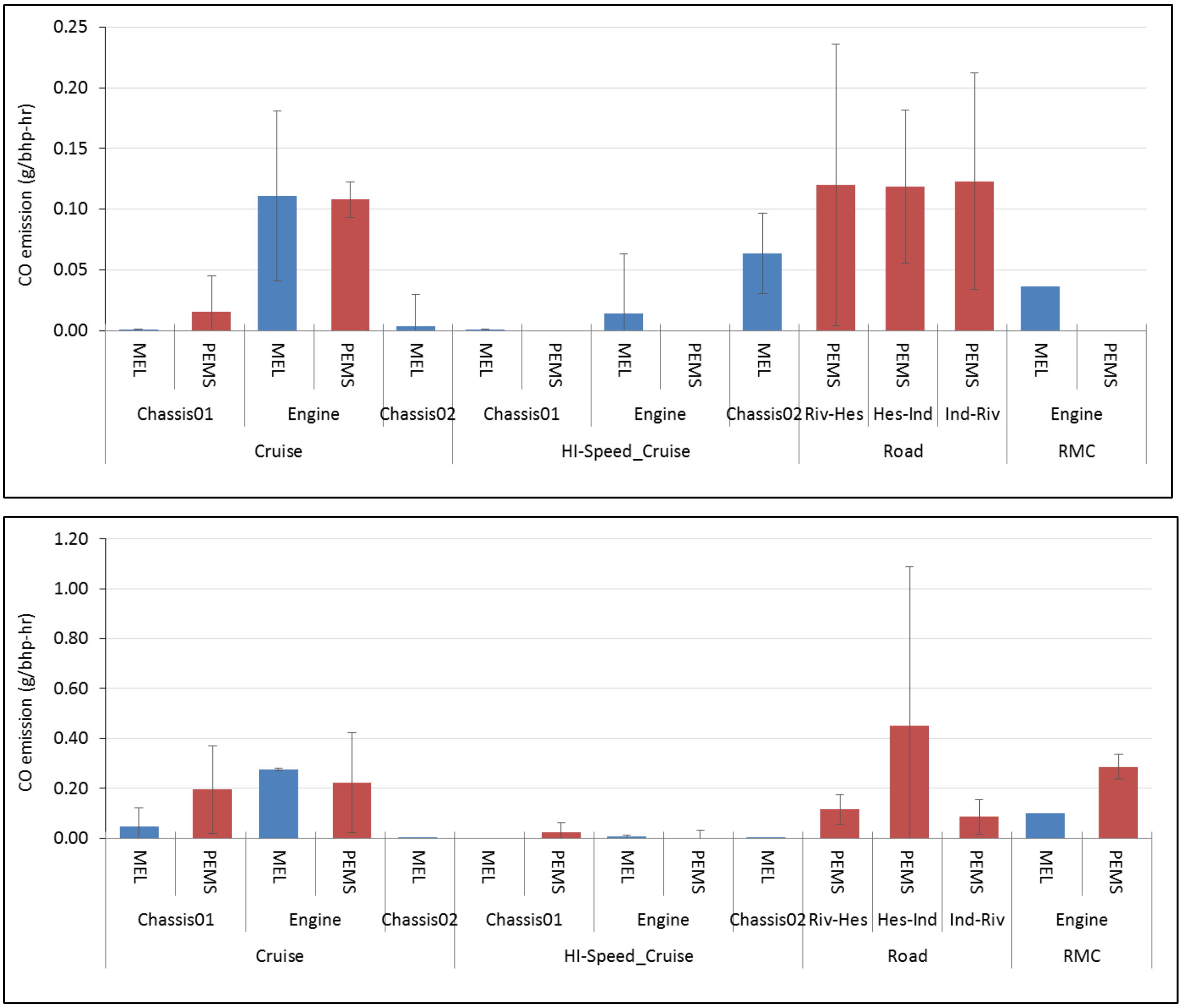


Figure 4-47. Average CO Emissions on a g/bhp-hr Basis for the Freeway and SET cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

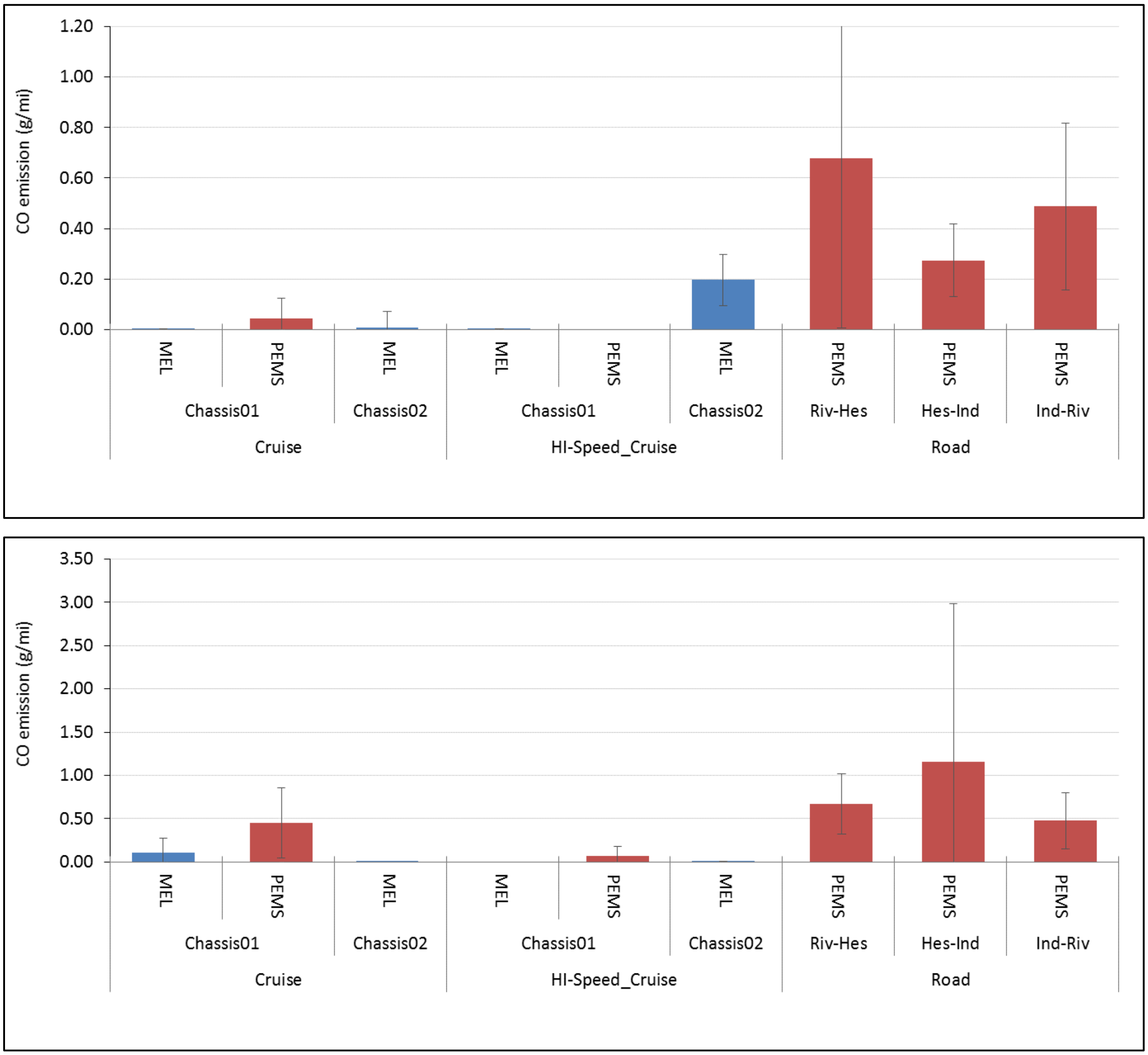


Figure 4-48 Average CO Emissions on a g/mi Basis for the Freeway and SET cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

4.4 THC Emissions

THC emissions for the Manufacturer A and Manufacturer B trucks are shown on a g/bhp-hr and a g/mi basis, respectively, in Figure 4-49 and Figure 4-50 for the urban driving cycles, including the CS-UDDS, UDDS, CS-FTP, FTP and HHDDT-transient cycles. THC emissions for the Manufacturer A and Manufacturer B trucks are shown on a g/bhp-hr and a g/mi basis, respectively, in Figure 4-51 and Figure 4-52 for the freeway driving cycles, including the cruise and high-speed cruise cycles as well as the results from the on-road and RMC engine dynamometer testing.

THC emissions were higher for the urban test cycles than the cruise/highway conditions. The emissions for the urban cycles ranged from 0.00 to 0.046 g/bhp-hr depending on the test point. The highest emissions were seen for the cold start tests, including the CS_UDDS and CS_FTP. The lowest THC emissions were seen for the on-road UDDS test. THC emissions for the highway cycles were all below 0.007 g/bhp/hr. On a g/mi basis, THC emissions ranged from 0.3 to 1.2 g/mi for the urban cycles and were all at or below 0.2 g/mi for the highway cycles.

In comparison with other studies, Jiang et al. (2018) found THC emissions were below 0.034 g/mi and 0.011 g/bhp-hr for five low mileage 2010 and newer vehicles over multiple cycles, except over the Creep cycle. The THC emission rates in this study were up to 0.04 g/bhp-hr for the Manufacturer A truck and 0.015 g/bhp-hr for the Manufacturer B truck, which were higher than the results from Jiang et al. (2018) study. A CARB (2015a, 2015b) study showed HC emissions that were below 0.050 g/mi for many vehicle/cycle combinations and consistent with the results of the hot start cycles of this study, although some vehicle/cycle points in the CARB study ranged from 0.117 to 1.442 g/mi. In a study by Miller et al. (2013), THC emission rates over the UDDS were 0.030 g/mi or less for most diesel trucks, which were much lower than the results of this study.

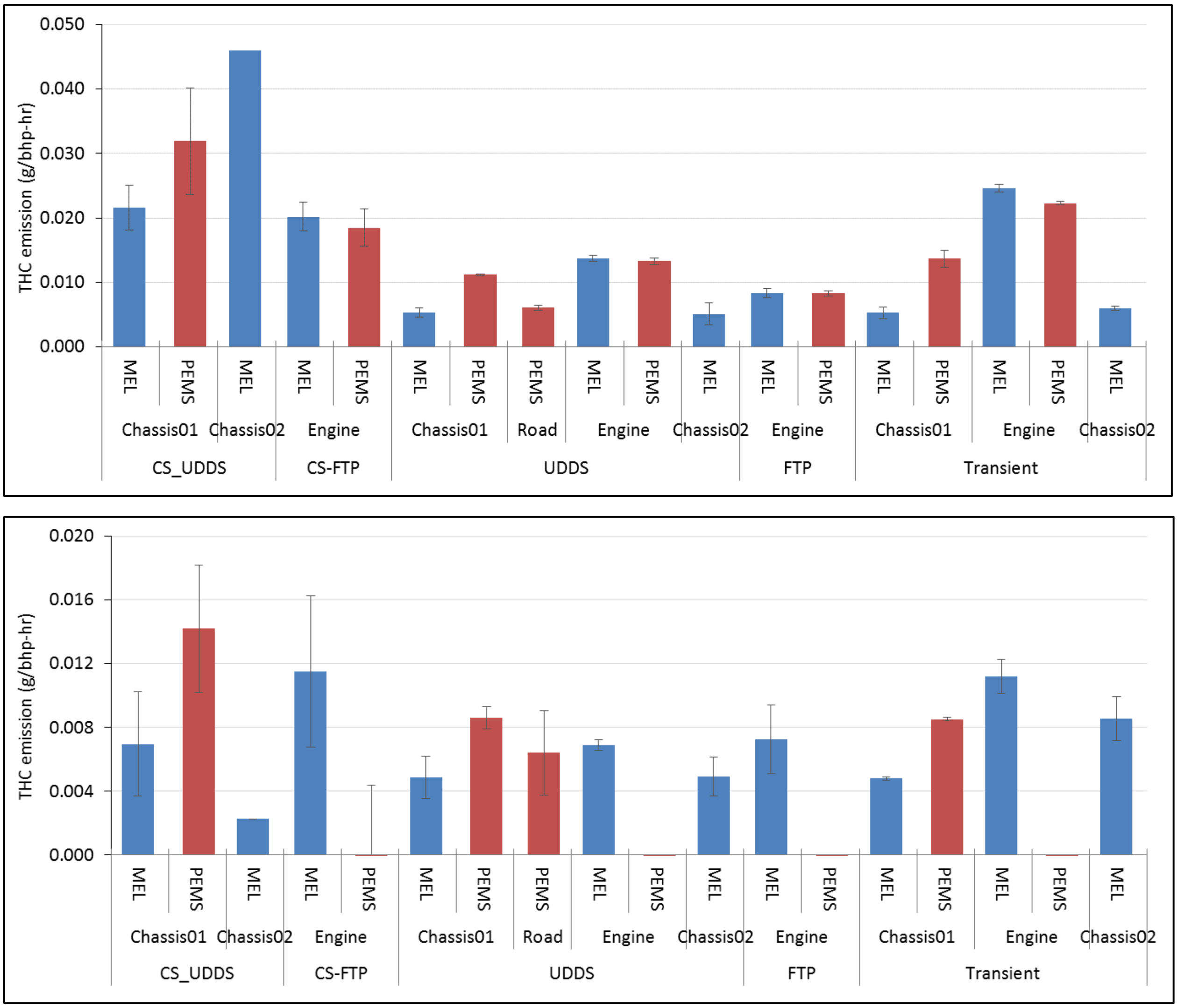
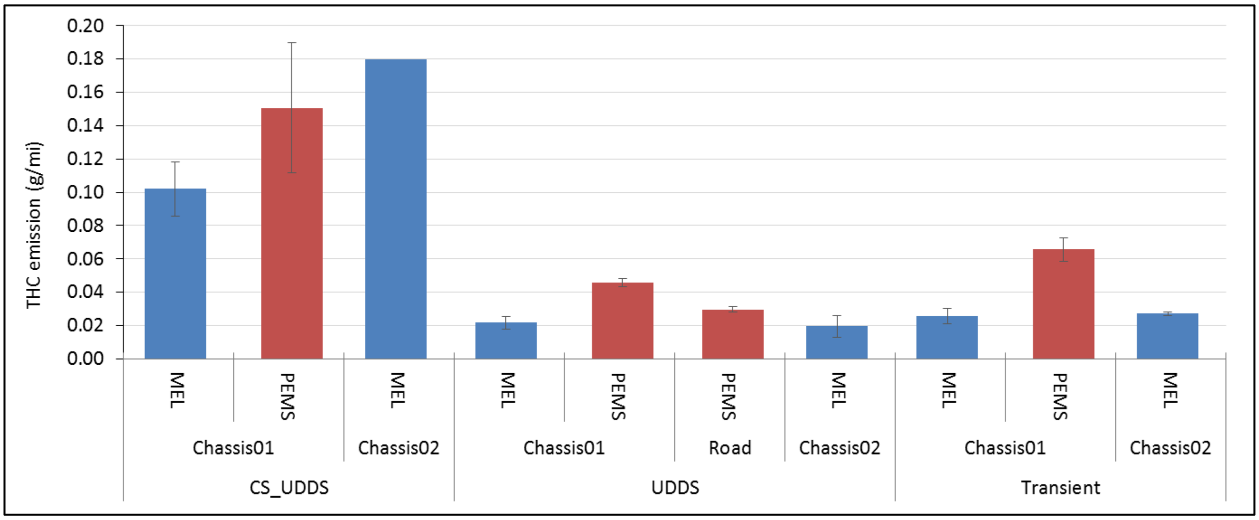


Figure 4-49. Average THC Emissions on a g/bhp-hr Basis for the urban cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)



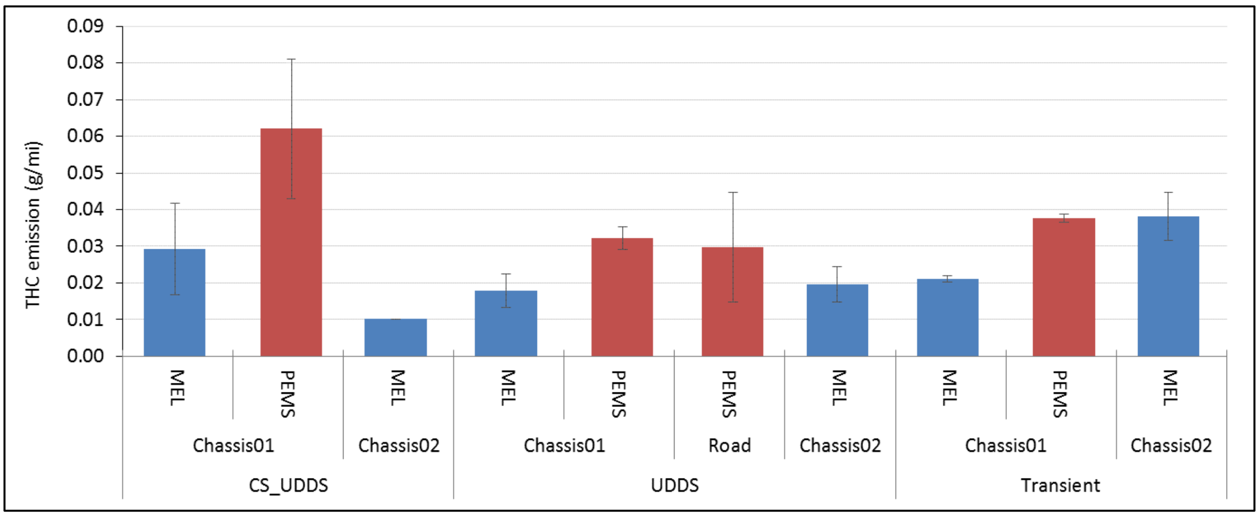


Figure 4-50 Average THC Emissions on a g/mi Basis for the urban cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

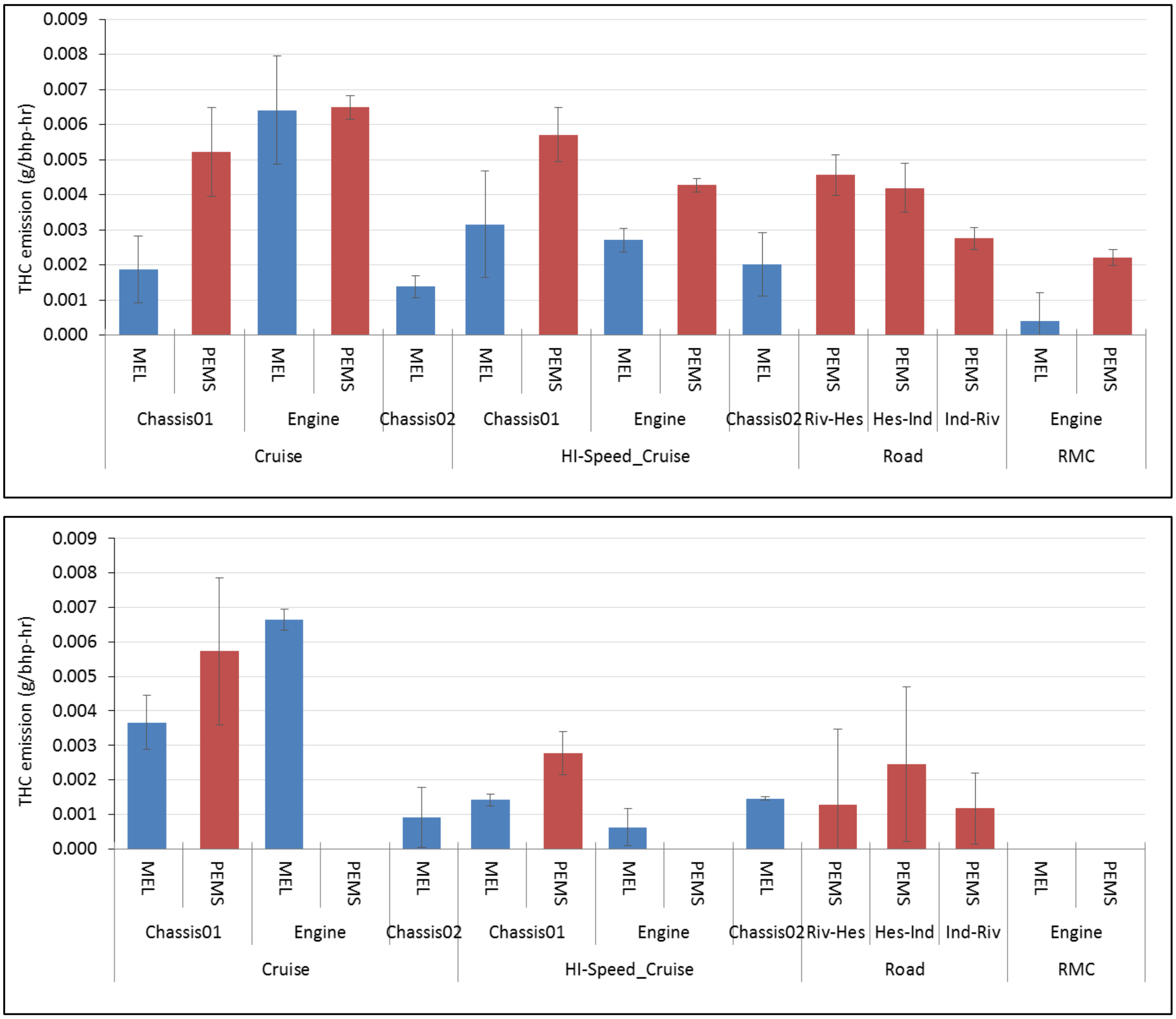


Figure 4-51. Average THC Emissions on a g/bhp-hr Basis for the Freeway and SET cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

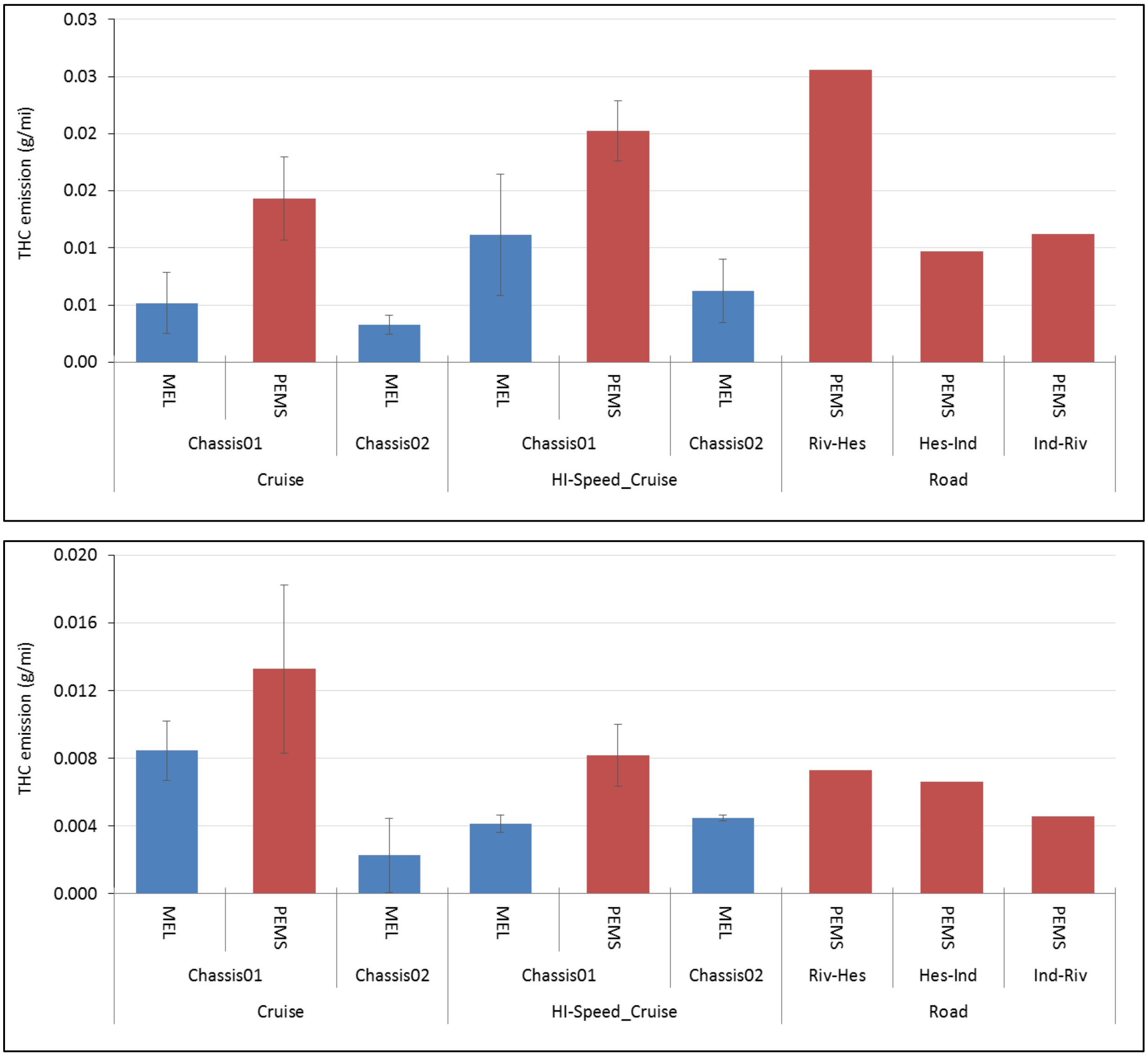


Figure 4-52 Average THC Emissions on a g/mi Basis for the Freeway and SET cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

4.5 CO_2 Emissions

4.5.1 CO_2 Emissions

CO_2 emissions for the Manufacturer A and Manufacturer B trucks are shown on a g/bhp-hr and a g/mi basis, respectively Figure 4-53 and Figure 4-54 and for the urban driving cycles, including the CS-UDDS, UDDS, CS-FTP, FTP and HHDDT-transient cycles. CO_2 emissions for the Manufacturer A and Manufacturer B trucks are shown on a g/bhp-hr and a g/mi basis, respectively, in Figure 4-55 and Figure 4-56 for the freeway driving cycles, including the cruise and high-speed cruise cycles as well as the results from the on-road and RMC engine dynamometer testing.

CO_2 emissions for the urban cycles generally ranged from 500 to 650 on a g/bhp-hr basis. This is slightly higher than the certification limits for the FTP with the recent greenhouse gas regulations. CO_2 emissions for the urban cycles generally ranged from ~2,200 to 2,700 on a g/mi basis, with the CO_2 emissions for the Transient cycle being slightly higher than those for the UDDS. The on-road UDDS CO_2 emissions were slightly below 500 g/bhp-hr for the Manufacturer A truck, but on a g/mi basis, the UDDS CO_2 emissions were similar for the chassis dynamometer and on-road tests. The CO_2 emissions for initial and final chassis dynamometer tests showed relatively good consistency, with the emissions being within 4% or less for the UDDS and Transient cycles.

CO_2 emissions on a g/bhp-hr basis were on the order of 450 to 550 g/bhp-hr for the freeway cycles, with slightly lower values for the high-speed cruise compared to the lower speed cruise cycle. The lowest CO_2 emissions on a g/bhp-hr were found for the on road testing between Riverside, Hesperia, and Indio. CO_2 emissions on a g/mi basis were in the range of 1500 to 1800 g/mi for the cruise and high speed cruise cycles, with higher emissions for the high speed cruise cycle. The CO_2 emissions for initial and final chassis dynamometer tests showed relatively good consistency, with the emissions being within 10% or less for the Cruise and Hi-Speed Cruise cycles. The on-road tests showed higher CO_2 emissions on a g/mi basis for the Riverside to Hesperia route, as this route include a steep uphill climb. The lowest CO_2 emissions on a g/mi basis were found for the Hesperia to Indio route, which includes long segments of downhill driving coming down from Hesperia.

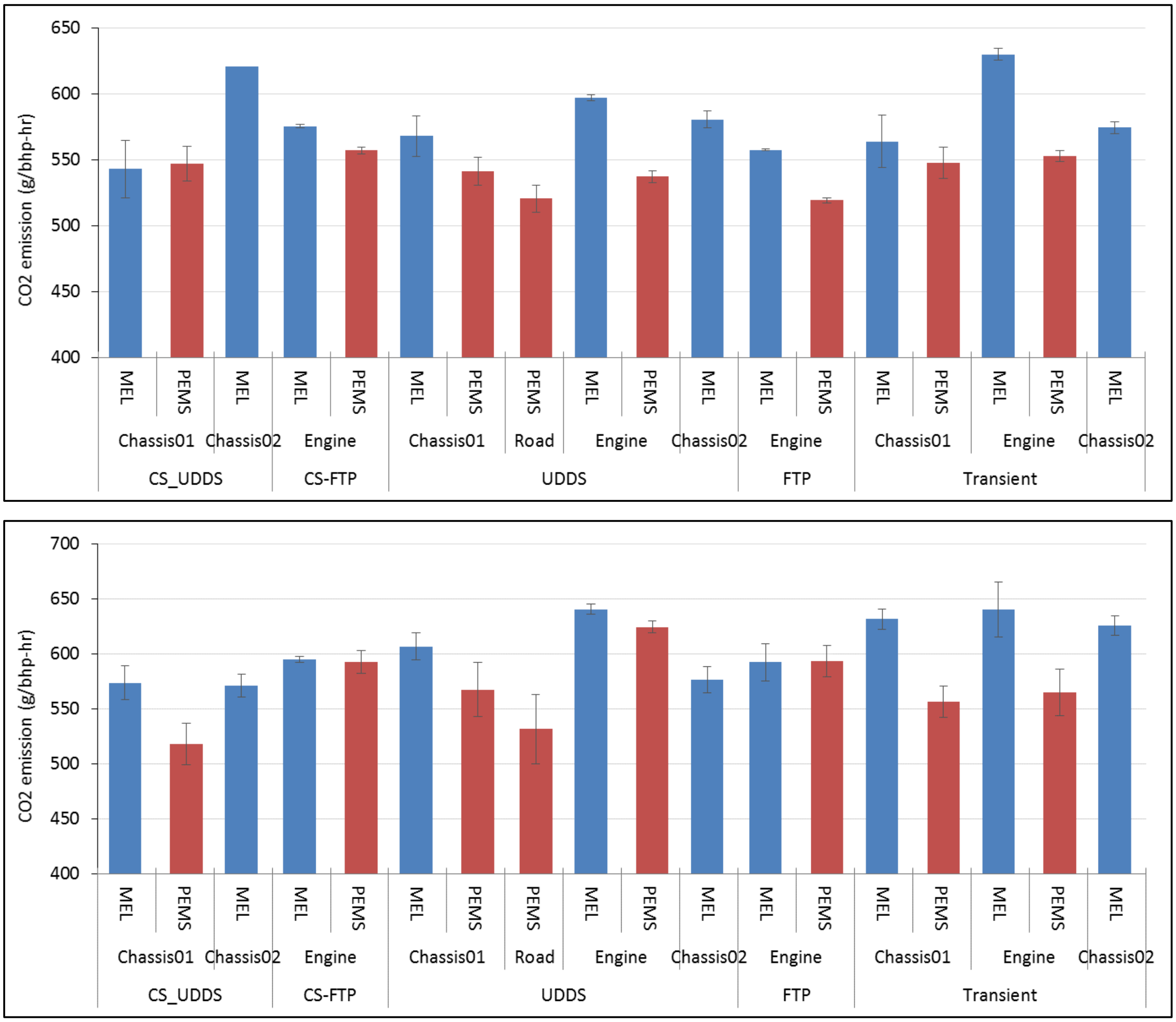


Figure 4-53. Average CO_2 Emissions on a g/bhp-hr Basis for the urban cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

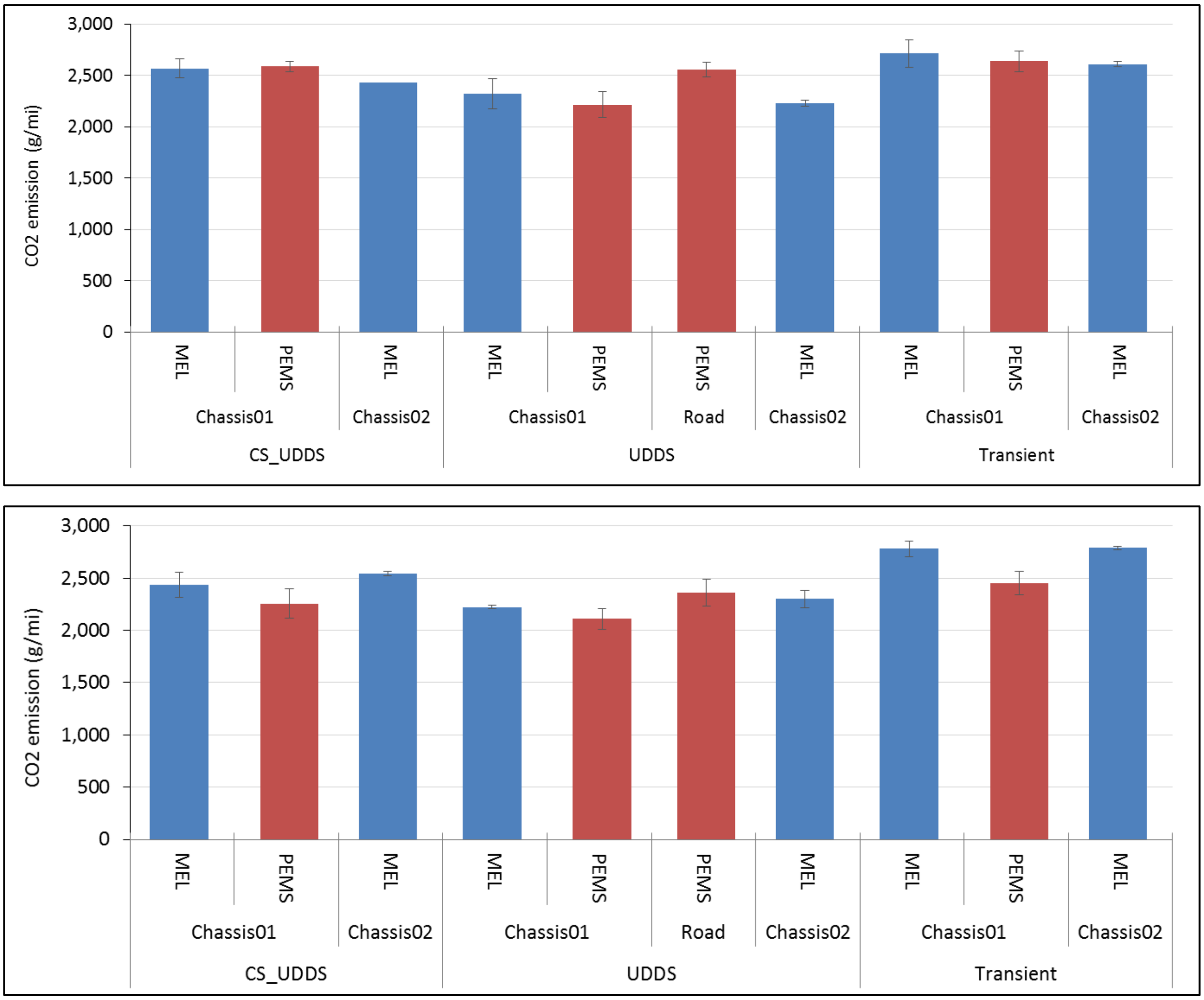
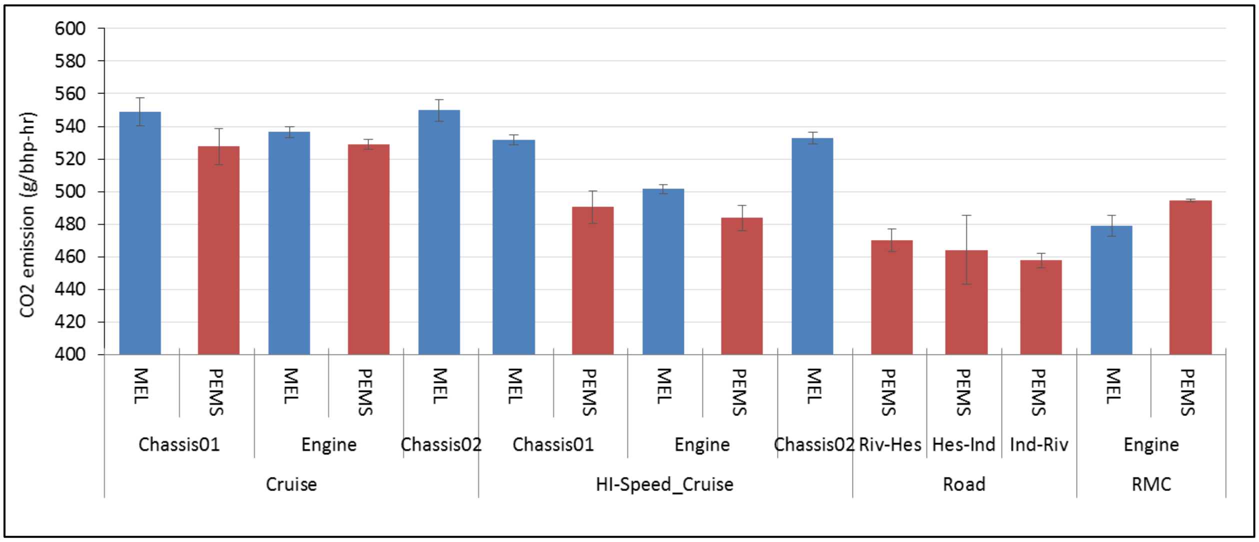


Figure 4-54. Average CO_2 Emissions on a g/mi Basis for the urban cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)



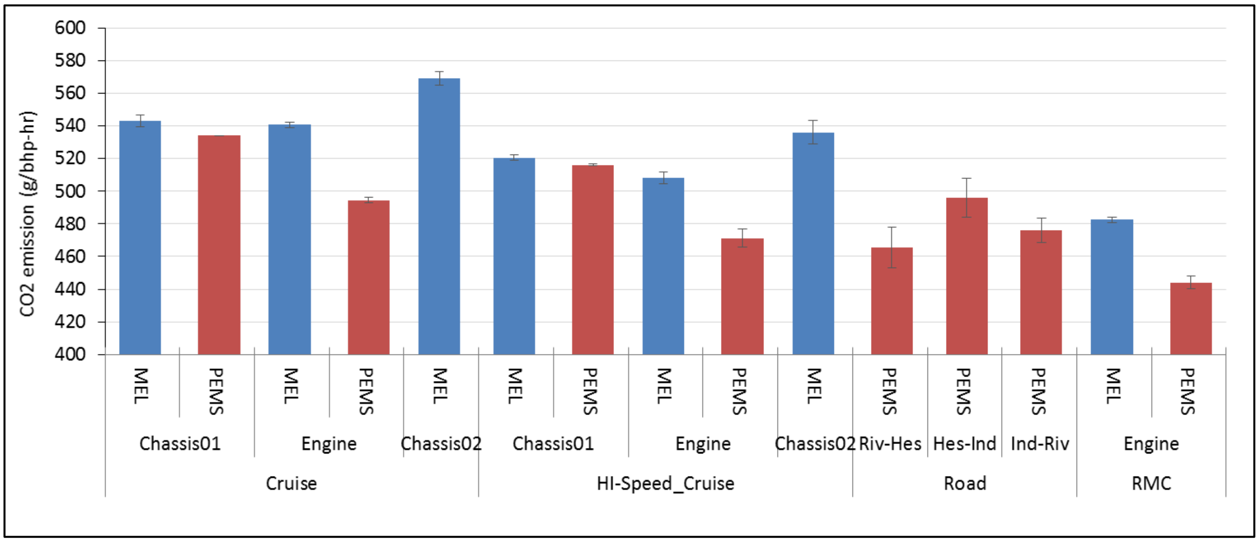
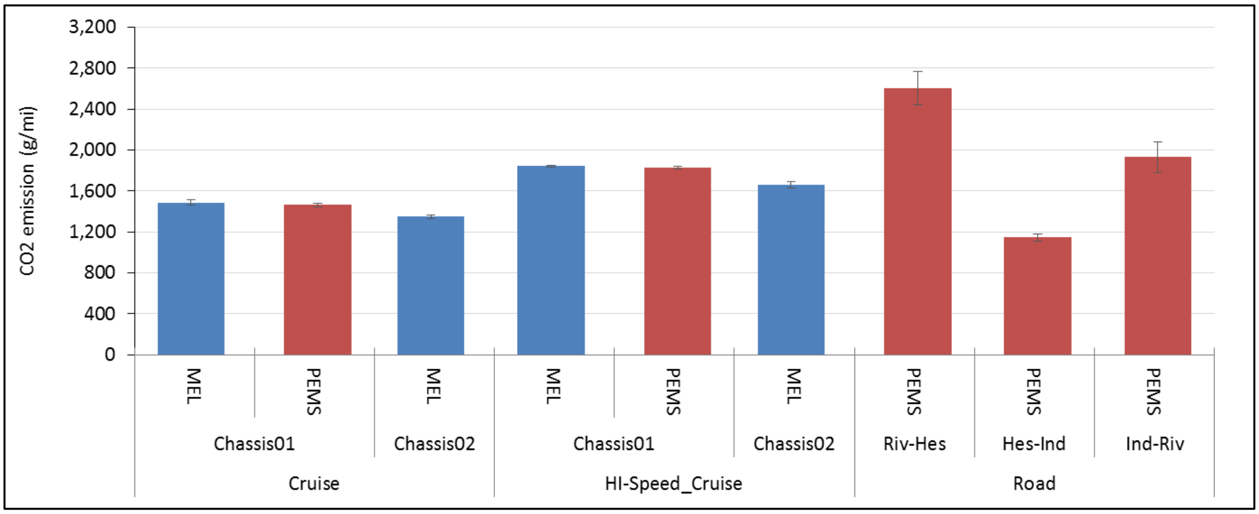


Figure 4-55 Average CO_2 Emissions on a g/bhp-hr Basis for the Freeway and SET cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)



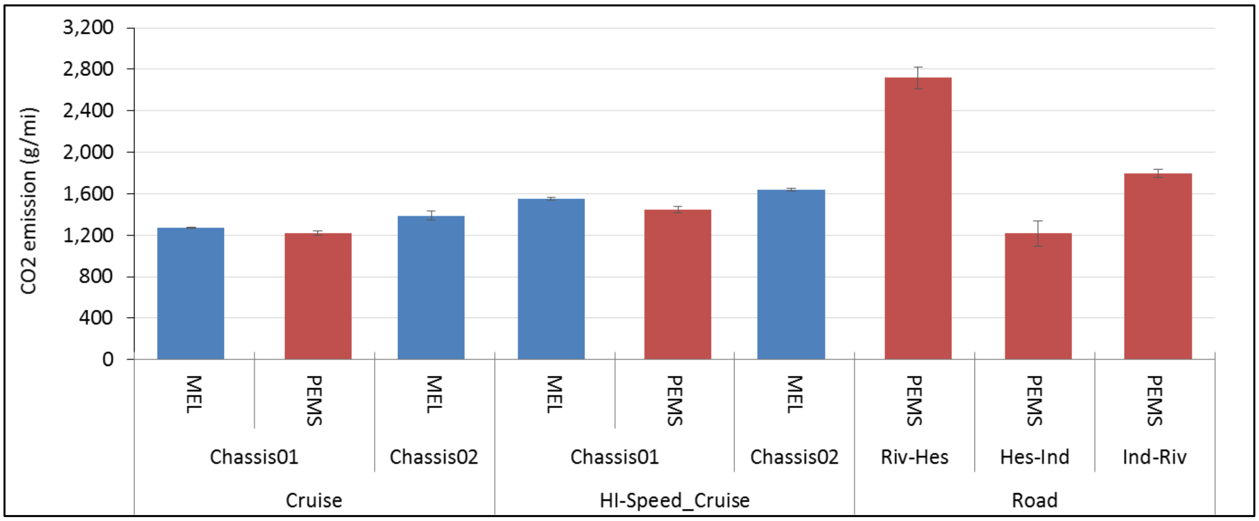


Figure 4-56 Average CO_2 Emissions on a g/mi Basis for the Freeway and SET cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

4.5.2 Carbon Balance

Table 4-2 and Table 4-3 provide a comparison of fuel consumption based on the fuel rate from the ECM and fuel consumption based on carbon balance from the emissions measurements for all test conditions for the Manufacturer A and Manufacturer B trucks, respectively. Note that the carbon balance calculations for the chassis 01, engine dynamometer and chassis 02 testing were based on MEL measurements and the carbon balance calculations for the on-road testing were based on PEMS measurements. For the Manufacturer A truck, the carbon balance fuel consumption was consistently higher than the fuel consumption based on the ECM, while the on-road testing carbon balance fuel consumption showed better agreement to the value from ECM since the exhaust flow rates of on-road testing were calculated based on intake air flow rate and fuel flow rate from ECM. Fuel consumption differences were within 10% or less for the Manufacturer A truck across the different laboratories. For the Manufacturer B truck, better agreement in fuel consumption was found between the fuel rate from the ECM and the carbon balance calculation, with differences being less than 5% for most cycles, except for the CS-UDDS for the chassis 01 testing, the UDDS for the on-road testing, and the Transient cycle for the engine dynamometer.

Table 4-2 Fuel Consumption Comparisons for the Manufacturer A Truck

Trace	Travel distance or power	ECM_Fuel consumed (gal)		Measurement_Fuel consumed (gal)		Difference
	mi or bhp-hr	Ave	Stdev	Ave	Stdev	
		Chassis 01				
CS_UDDS	5.4*	1.3	0.0	1.4	0.0	5%
UDDS	5.6	1.2	0.0	1.3	0.1	10%
Transient	2.7	0.7	0.1	0.7	0.1	8%
HI-Speed_Cruise	23.0	1.8	0.0	1.9	0.0	8%
HHDDT Cruise	10.5	3.1	0.0	3.4	0.1	9%
		On-road				
UDDS	5.2*	1.3	0.0	1.3	0.0	0%
CE-CERT-Hesperia	36.9	9.9	0.5	9.6	0.6	-3%
Hesperia-Indio	103.8	12.0	0.6	11.9	0.4	-1%
Indio-CE-CERT	79.1	15.1	1.4	15.2	1.3	1%
		Engien dyno				
CS_FTP	29.0#	1.7	0.0	1.7	0.0	0%
FTP	29.0	1.5	0.0	1.6	0.0	4%
UDDS	22.1	1.3	0.0	1.3	0.0	5%
Transient	9.9	0.6	0.0	0.6	0.0	7%
ARB_HS_CruiseHDD	33.2	1.6	0.0	1.7	0.0	3%
ARB_CruiseHDD	62.1	3.2	0.0	3.3	0.0	4%
RMC_post2010	139.8	6.5	0.0	6.7	0.0	4%
		Chassis 02				
CS_UDDS	5.5*	1.3		1.3		5%
UDDS	5.5	1.1	0.0	1.2	0.0	10%
Transient	2.8	0.7	0.0	0.7	0.0	9%
HI-Speed_Cruise	23.0	1.6	0.0	1.7	0.0	6%
HHDDT Cruise	10.4	2.8	0.0	3.1	0.0	9%

*represents the distance results for the chassis 01, on-road and chassis 02. # represents the work results for the engine dynamometer.

Table 4-3 Fuel Consumption Comparisons for the Manufacturer B Truck

Trace	Travel distance or power mi or bhp-hr	ECM_Fuel consumed (gal) Ave	Stdev	Measurement_Fuel consumed (gal) Ave	Stdev	Difference
		Chassis 01				
CS_UDDS	5.5*	1.5	0.1	1.3	0.1	-11%
UDDS	5.6	1.2	0.1	1.3	0.0	1%
Transient	2.8	0.8	0.1	0.8	0.0	-5%
HI-Speed_Cruise	23.1	1.6	0.0	1.6	0.0	4%
HHDDT Cruise	10.5	2.7	0.1	2.9	0.0	6%
		On-road				
UDDS	5.1*	1.4	0.1	1.2	0.1	-16%
CE-CERT-Hesperia	37.5	10.6	0.7	10.2	0.3	-5%
Hesperia-Indio	97.2	12.3	0.8	11.8	1.2	-4%
Indio-CE-CERT	74.4	14.4	0.5	13.3	0.6	-8%
		Engien dyno				
CS_FTP	31.1#	1.8	0.0	1.8	0.0	1%
FTP	31.3	1.8	0.1	1.9	0.0	3%
UDDS	22.0	1.4	0.0	1.4	0.0	1%
Transient	10.7	0.7	0.0	0.6	0.0	-11%
ARB_HS_CruiseHDD	37.2	1.8	0.0	1.8	0.0	0%
ARB_CruiseHDD	67.4	3.5	0.0	3.6	0.0	3%
RMC_post2010	152.8	7.2	0.0	7.5	0.0	5%
		Chassis 02				
CS_UDDS	5.6*	1.4	0.0	1.4	0.1	-1%
UDDS	5.5	1.3	0.0	1.3	0.1	3%
Transient	2.8	0.8	0.0	0.9	0.0	9%
HI-Speed_Cruise	23.1	1.7	0.0	1.7	0.0	-4%
HHDDT Cruise	10.6	3.2	0.1	3.1	0.1	-5%

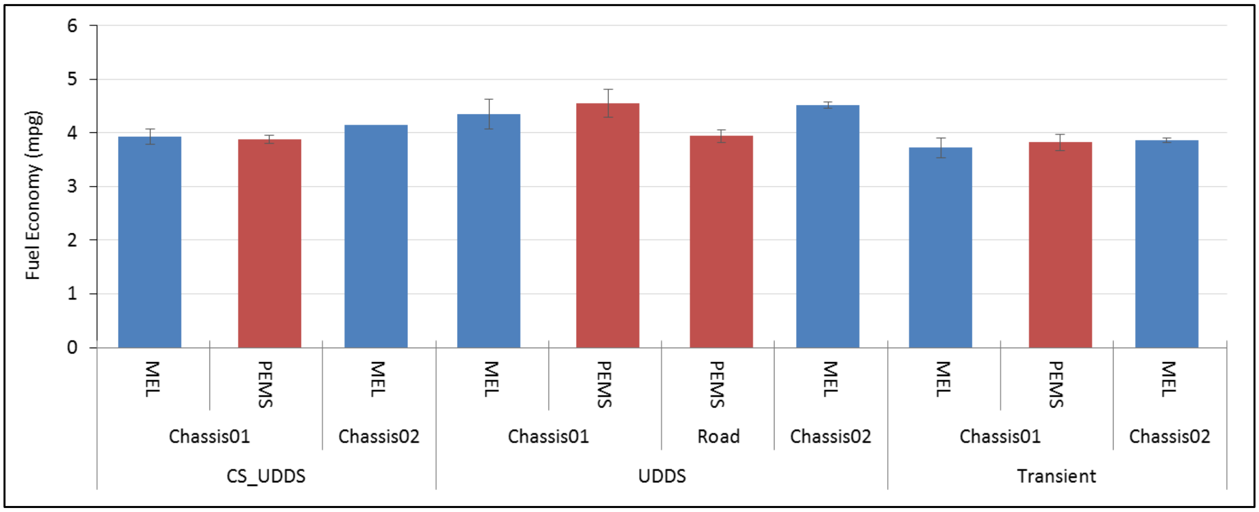
*represents the distance results for the chassis 01, on-road and chassis 02. # represents the work results for the engine dynamometer. Note that the frequency for the Manufacturer B engine fuel rate from the ECM was 0.2 Hz.

4.6 Fuel Economy

Fuel economy results for the Manufacturer A and Manufacturer B trucks are shown in Figure 4-57 for the urban driving cycles, including the CS-UDDS, UDDS, and HHDDT-transient cycles. Fuel economy results for the Manufacturer A and Manufacturer B trucks are shown in Figure 4-58 for the freeway driving cycles, including the cruise and high-speed cruise cycles as well as the results from the on-road testing.

Fuel economy for the urban cycles generally ranged from 3.6 to 4.8 mpg, with the fuel economy for the Transient cycle being slightly lower than those for the UDDS, consistent with the CO_2 emissions being slightly higher for the Transient cycle. The fuel economy for the on-road UDDS was similar to the results from the chassis dynamometer testing. The fuel economy for initial and final chassis dynamometer tests showed relatively good consistency, with the differences being 3.9% or less for the UDDS and Transient cycles.

Fuel economies were on the order of 3.7 to 9.0 mpg for the freeway cycles, with slightly higher values for the high-speed cruise compared to the lower speed cruise cycle. The highest fuel economy was found for the on road testing between Riverside, Hesperia, and Indio. Fuel economies were in the range of 5.5 to 8.2 mpg for the cruise and high speed cruise cycles, with a higher fuel economy for the cruise cycle. The fuel economies for initial and final chassis dynamometer tests were within 11% or less for the Cruise and Hi-Speed Cruise cycles. The on-road tests showed lower fuel economy for the Riverside to Hesperia route, as this route include a steep uphill climb. The highest fuel economy was found for the Hesperia to Indio route, which includes long segments of downhill driving coming down from Hesperia.



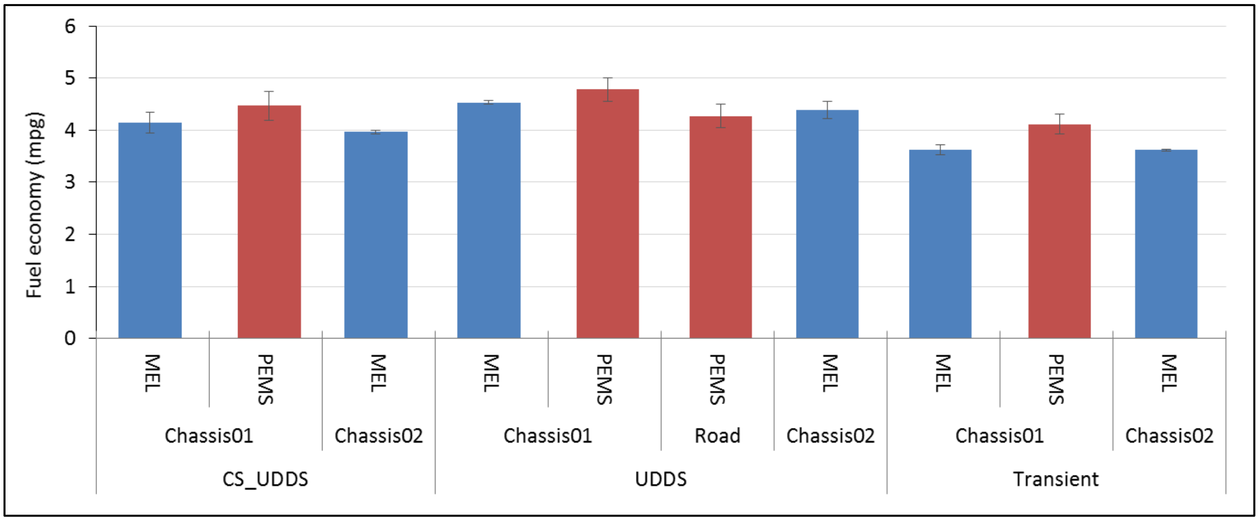
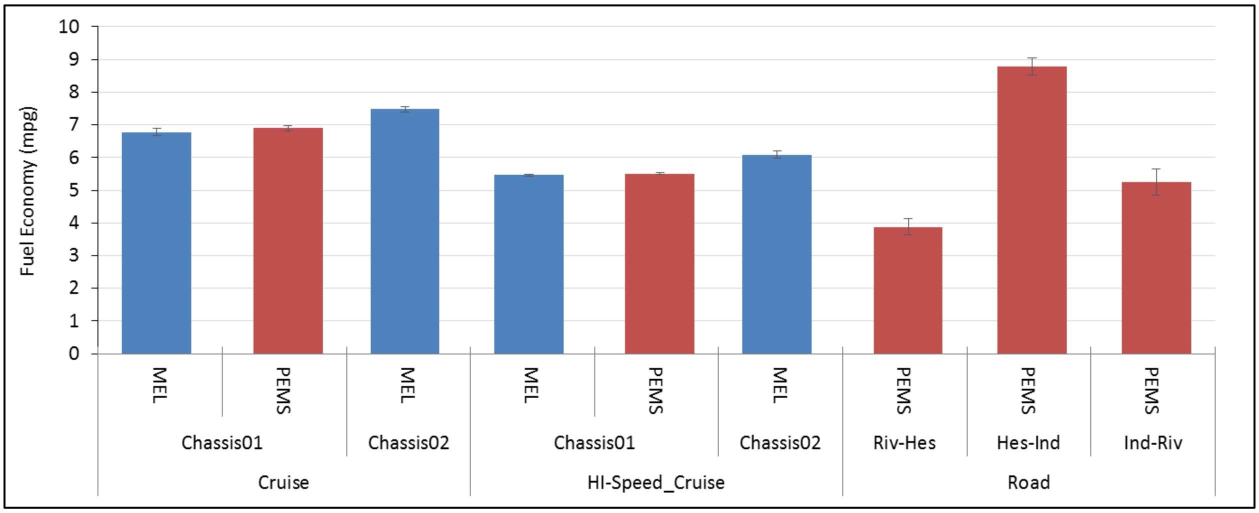


Figure 4-57 Average fuel economy for the urban cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)



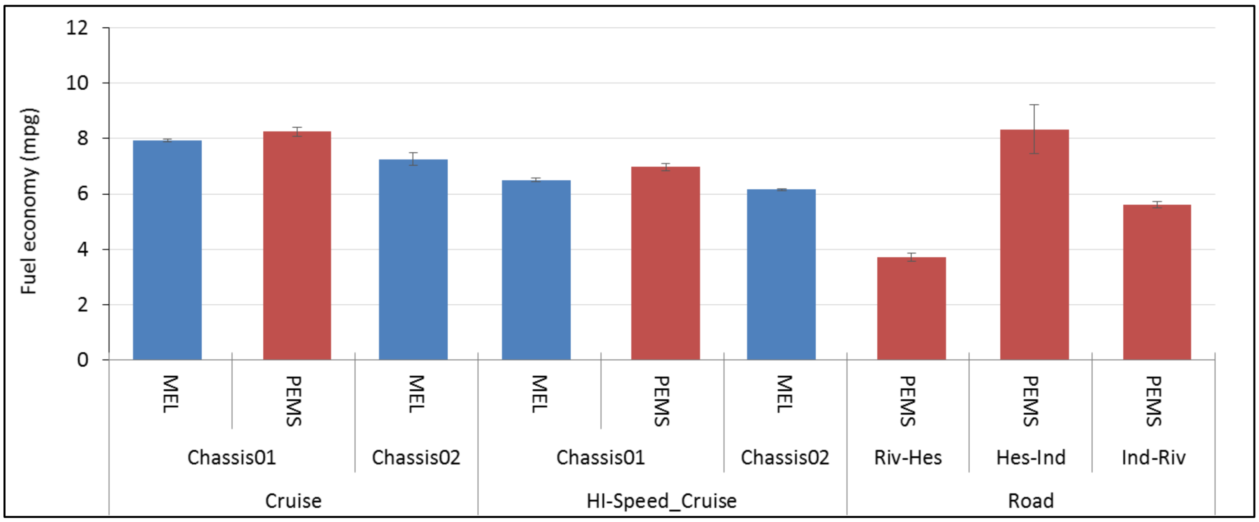


Figure 4-58 Average fuel economy for the urban cycles for the Manufacturer A Truck (Top) and Manufacturer B Truck (bottom)

5 Data Analysis for In-Use Compliance Methodologies

An important element of this program was the evaluation of in-use compliance methodologies. For this study, two main in-use compliance test methodologies were evaluated. This includes the not-to-exceed (NTE) method and the Moving average window (MAW). Results of analyses based on this methods are discussed for both the on-road and the chassis dynamometer testing in this section.

5.1 NTE Analysis

The NTE analysis is based on quantifying emissions for driving where the engine is operating in the NTE control area or zone. For regulatory requirements, operation in the NTE zone for a period of at least 30 seconds is required to create a valid NTE event. The specifications of the NTE zone are discussed in greater detail in section 2.1.3.1. In this subsection, NTE analyses are for both the on-road and chassis dynamometer testing results.

5.1.1 On-Road Testing

5.1.1.1 <u>30% Max power and 30% Max Torque</u>

NTE analyses were conducted separately for the three main on-road driving segments, including Riverside to Hesperia, Hesperia to Indio, and Indio to Hesperia since the routes were often tested on different test days. A summary of NOx emission rates in the NTE zone, valid NTE events and non-NTE zone is provided in Figure 5-1. A summary of the activity statistics for the three routes is provide Table 5-1 to Table 5-3 for the Manufacturer A Truck and Table 5-6 to Table 5-8 for the Manufacturer B truck. The results of the basic NTE analyses with and without the measurement allowance are provided in Table 5-4 and Table 5-5 for the Manufacturer A truck and in Table 5-9 and Table 5-10 for the Manufacturer B truck, respectively. Figure 5-3 and Figure 5-5 show the altitude and where the NTE events happened of one test route for the Manufacturer A and Manufacturer B trucks, respectively.

Figure 5-1 shows that NOx emissions outside the NTE zone for both vehicles were significantly higher than those in the NTE zone. NOx emissions for the failed NTE events were higher than those passing NTE events. NOx emission rates during passing NTE events were lower than those for overall activity in the NTE zone and for the whole trip for the Manufacturer A truck. NOx emission rates for passing NTE events were comparable to those of overall activity in the NTE zone, but were lower than the values for the whole trip for the Manufacturer B truck.

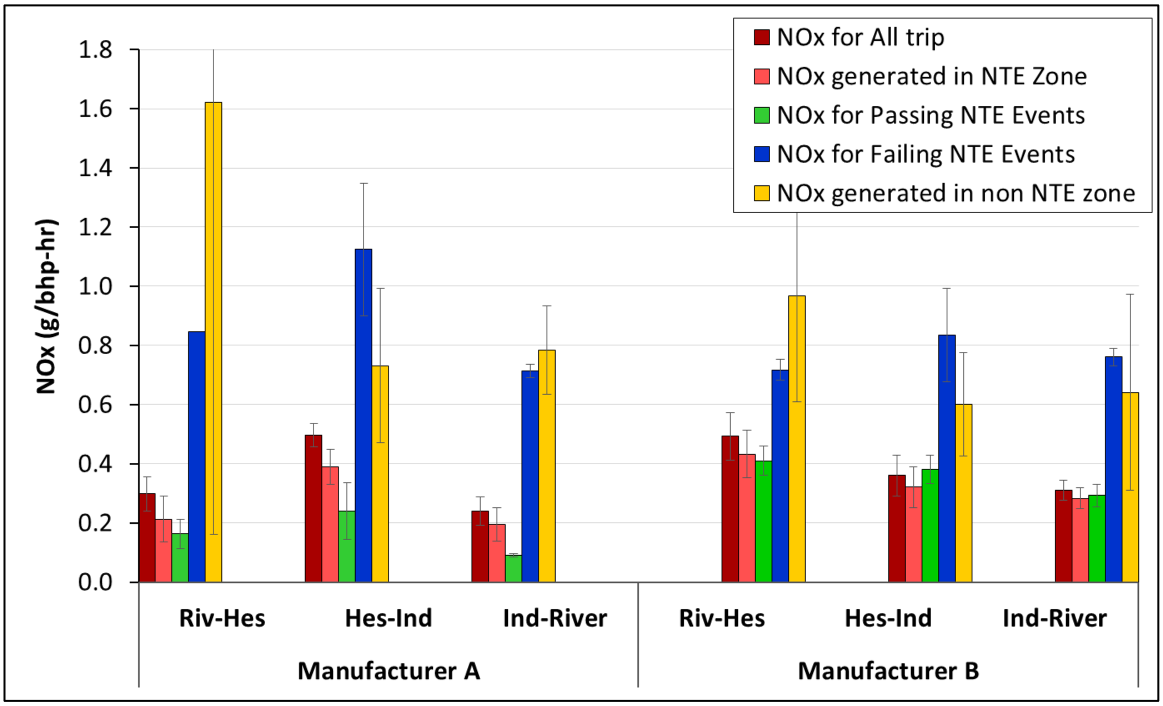


Figure 5-1 NOx emission rates of NTE zone, valid NTE events and non NTE zone

Figure 5-2 shows the distribution of load points for engine RPM and torque for the on-road testing for both trucks. The results show that a majority of the operation was between 1300 and 1700 rpm for the Manufacturer A engine and between 1000 and 1500 rpm for the Manufacturer B engine. Within the RPM ranges for the two engines, there was a broad distribution of torque values for the test data for the entire trip, as well for operation in the NTE zone, for valid NTE events, and for failed NTE events. There was a greater tendency for the failed NTE events for the Manufacturer B truck to be near the peak torque for a given engine speed, but otherwise, there did not seem to be any particular load points that were especially prone to failing the NTE test.

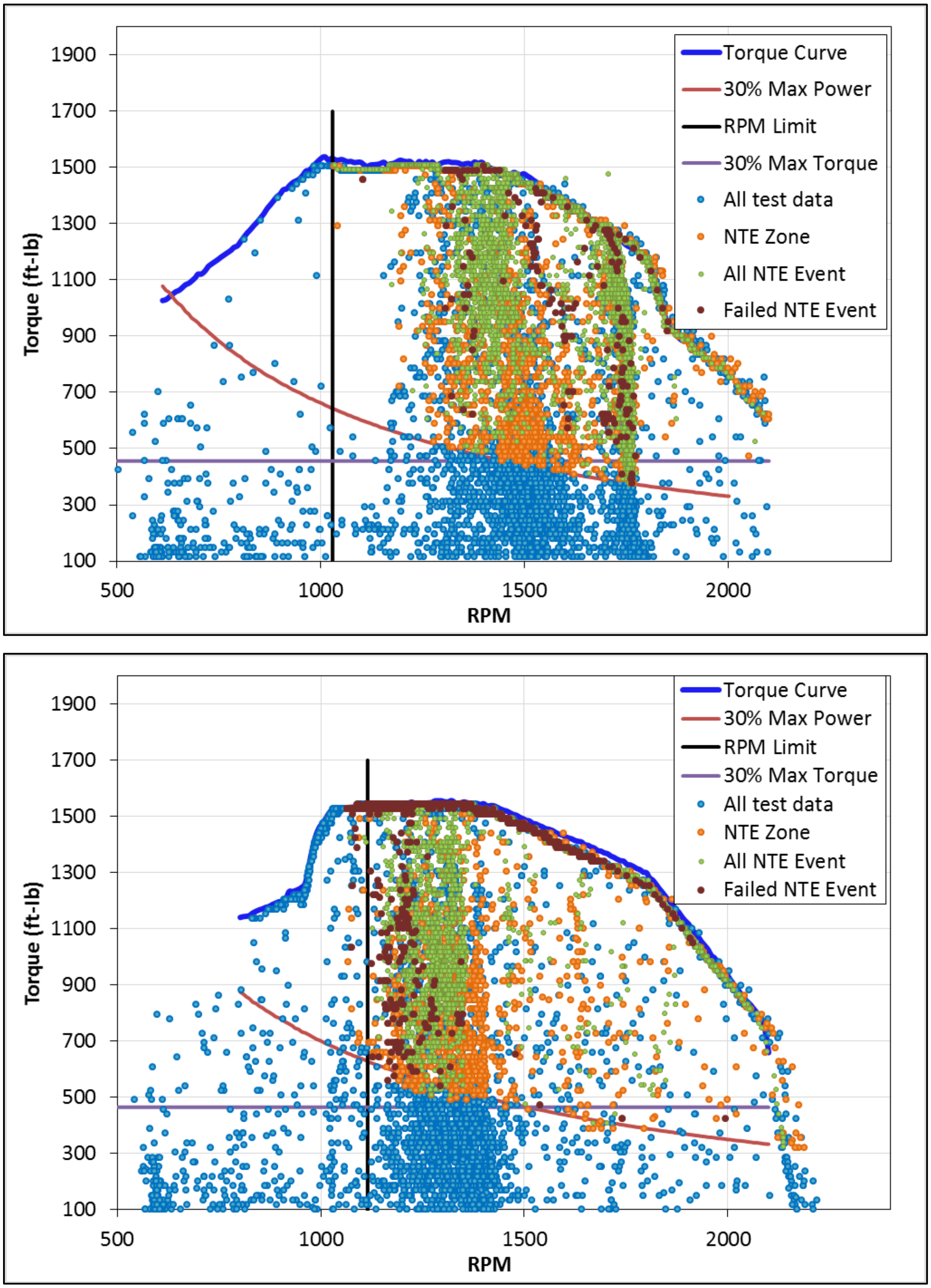


Figure 5-2 RPM and torque map of on-road testing for the Manufacturer A Truck (top) and Manufacturer B Truck (bottom)

The activity analysis for the Manufacturer A truck show the differences between the different routes. The Hesperia to Indio and Indio to Riverside route have average speeds between 47 and 54 mph. Slower speeds were found for the Riverside to Hesperia route as this route features a significant uphill climb up the Cajon pass. The highest emissions were found for the Hesperia to Indio route (0.50 g/bhp-hr), followed by the Riverside to Hesperia route (0.31 g/bhp-hr), with the

Indio to Riverside route showing the lowest emissions (0.23 g/bhp-hr). The highest power was found for the Indio to Riverside route (321 bhp-hr), followed by the Hesperia to Indio route (240 bhp-hr), with the Riverside to Hesperia route showing the lowest emissions (207 bhp-hr). The lower power for the Riverside to Hesperia route is probably due to the shorter route in terms of distance and time, as this route did have the steepest incline. In terms of operation in the NTE zone, the Indio to Riverside had the highest percentage of activity in the NTE zone (57%), compared to 52% for the Riverside to Hesperia route, and 28% for the Hesperia to Indio route. The Indio to Riverside route had the highest percentage of activity spent in valid NTE events (42%), compared to 36% for the Riverside to Hesperia route, and 10% for the Hesperia to Indio route.

The breakdown of NOx emissions between the NTE and non-NTE operation varied between the different routes. For the Riverside to Hesperia route the highest fraction of NOx was found for the valid NTE events (32.2%), with another 29.2% of the NOx coming from NTE zone operation that did not qualify as an NTE event due to temperature <250°C or the duration being < 30 seconds, with only 12.9% of NOx emissions found during non-NTE operation. There was also a significant fraction of NOx generated under cold operation for the Riverside to Hesperia route, but this appeared to be primarily due to a single test where 63.4% of the NOx was generated under cold conditions.

For the Hesperia to Indio route showed a much lower fraction of NOx generated during valid NTE events (15%), with another 33.1% of the NOx coming from NTE zone operation that did not qualify as an NTE event due to temperature <250°C or the duration being < 30 seconds. Still, only 18.1% of NOx was formed for operation outside the NTE zone. The highest fraction of NOx was generated under cold operation (33.8%), although this varied significantly from test to test.

For the Indio to Riverside route, a higher fraction of NOx was generated during valid NTE events (27.1%), with another 43.6% of the NOx coming from NTE zone operation that did not qualify as an NTE event due to temperature <250°C or the duration being < 30 seconds. Only 17.2% of NOx was formed during non-NTE zone operation and only 12.1% of NOx was formed under cold operation conditions.

Table 5-1 NTE Activity analysis for Manufacturer A (CERT-Hes)

	Route ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	75	3744	34	35	207	0.36		
	2	60	3643	36	37	214	0.28		
	3	50	2923	45	37	199	0.25		
	Ave	62	3437	39	36	207	0.30		
Cold Operation	1	4	67	45	1	7	0.57	5.0	1.8
	2	38	1280	38	13	89	0.43	63.4	35.1
	3	3	95	50	1	9	0.35	6.3	3.3
	Ave	15	481	44	5	35	0.45	24.9	13.4
Non-NTE	1	13	1680	18	8	9	1.56	17.8	44.9
	2	1	1059	21	6	5	0.19	1.7	29.1
	3	17	916	35	9	6	3.11	34.9	31.3
	Ave	11	1218	25	8	6	1.62	18.1	35.1
Invalid NTE Events, <250C	1	23	200	26	1	16	1.43	30.6	5.3
	2	1	28	31	0	2	0.50	1.8	0.8
	3	11	165	32	1	12	0.94	22.7	5.6
	Ave	12	131	30	1	10	0.95	18.4	3.9
Invalid NTE Events, <30s & >250C	1	7	327	48	4	28	0.26	9.9	8.7
	2	7	620	47	8	51	0.13	11.4	17.0
	3	2	253	58	4	19	0.09	3.4	8.7
	Ave	5	400	51	5	33	0.16	8.2	11.5
Valid NTE Events	1	28	1470	50	20	148	0.19	36.8	39.3
	2	13	656	48	9	66	0.20	21.7	18.0
	3	16	1494	51	21	153	0.11	32.6	51.1
	Ave	19	1207	50	17	123	0.16	30.4	36.1

Table 5-2 NTE Activity analysis for Manufacturer A (Hes-Ind)

	Route ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	128	7161	52	104	239	0.54		
	2	122	6969	54	104	247	0.50		
	3	107	6809	55	103	234	0.46		
	Ave	119	6980	54	104	240	0.50		
Cold Operation	1	25	1080	53	16	19	1.26	19.2	15.1
	2	71	2481	56	39	112	0.64	58.2	35.6
	3	25	1390	57	22	63	0.39	23.1	20.4
	Ave	40	1650	55	26	65	0.76	33.5	23.7
Non-NTE	1	18	3634	52	53	30	0.61	14.4	50.7
	2	16	2963	51	42	29	0.56	13.1	42.5
	3	25	3452	54	52	24	1.03	23.3	50.7
	Ave	20	3350	52	49	28	0.73	17.0	48.0
Invalid NTE Events, <250C	1	35	445	52	6	26	1.36	27.6	6.2
	2	20	349	55	5	21	0.98	16.7	5.0
	3	31	530	54	8	31	1.00	29.3	7.8
	Ave	29	441	54	7	26	1.11	24.5	6.3
Invalid NTE Events, <30s & >250C	1	14	768	53	11	51	0.27	10.8	10.7
	2	11	895	57	14	58	0.19	9.0	12.8
	3	10	791	57	13	55	0.17	9.0	11.6
	Ave	11	818	56	13	54	0.21	9.6	11.7
Valid NTE Events	1	36	1234	52	18	113	0.32	28.1	17.2
	2	4	281	51	4	27	0.13	2.9	4.0
	3	16	646	51	9	61	0.27	15.3	9.5
	Ave	19	720	51	10	67	0.24	15.4	10.3

Table 5-3 NTE Activity analysis for Manufacturer A (Ind-CERT)

	Route ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	78	6107	47	80	353	0.22		
	2	91	6608	43	79	306	0.30		
	3	62	5654	50	79	304	0.20		
	Ave	77	6123	47	79	321	0.24		
Cold Operation	1	17	660	59	11	27	0.64	22.0	10.8
	2	11	576	55	9	22	0.53	12.6	8.7
	3	1	49	56	1	2	0.50	1.9	0.9
	Ave	10	428	57	7	17	0.55	12.1	6.8
Non-NTE	1	12	1914	33	18	14	0.82	14.9	31.3
	2	9	2603	29	21	15	0.62	10.5	39.4
	3	13	2177	43	26	14	0.91	20.6	38.5
	Ave	11	2231	35	22	15	0.78	15.3	36.4
Invalid NTE Events, <250C	1	21	285	40	3	21	0.97	26.7	4.7
	2	38	338	39	4	25	1.55	42.5	5.1
	3	22	220	45	3	18	1.24	35.3	3.9
	Ave	27	281	41	3	21	1.25	34.8	4.6
Invalid NTE Events, <30s & >250C	1	7	541	49	7	40	0.19	9.5	8.9
	2	11	426	47	6	29	0.37	11.8	6.4
	3	7	818	53	12	59	0.12	11.3	14.5
	Ave	8	595	50	8	43	0.23	10.9	9.9
Valid NTE Events	1	21	2707	54	41	250	0.08	26.9	44.3
	2	21	2665	54	40	216	0.10	22.7	40.3
	3	19	2390	56	37	211	0.09	30.9	42.3
	Ave	20	2587	55	39	226	0.09	26.8	42.3

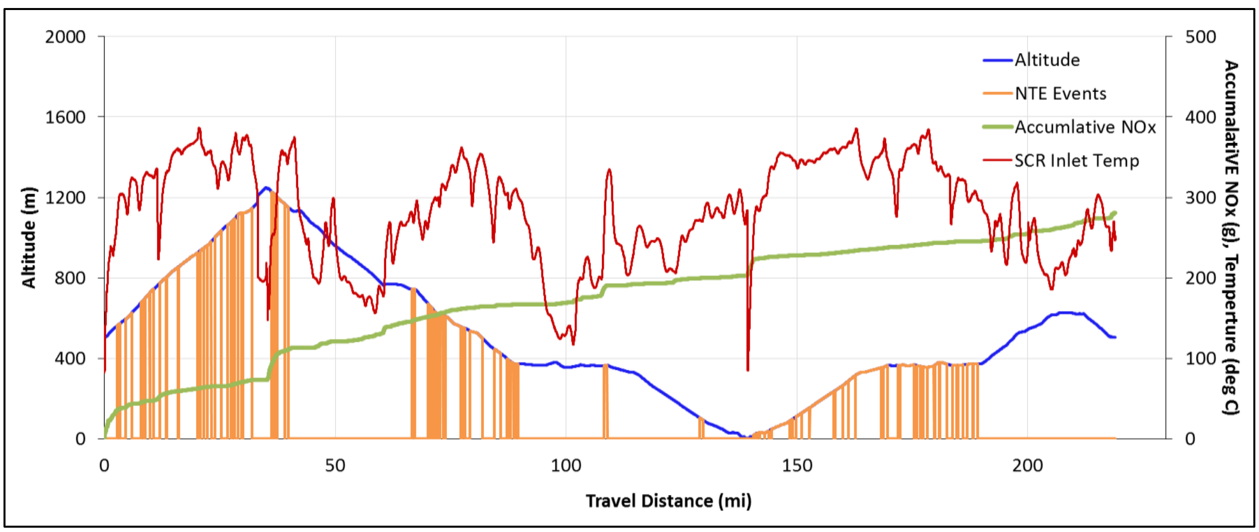


Figure 5-3 Altitude vs NTE event for one test route (Riv-Hes-Indi-Riv) for the Manufacturer A truck

The emissions were evaluated based on the standard NTE criteria. For 2010 and newer trucks, the passing criteria for the NTE test is that at least 90% of time-weighted NTE pass events should be below a threshold 0.45 g/bhp-hr for NOx, based on 1.5 times the certification standard + 0.15 g/bhp-hr (PEMS accuracy margin). For the Manufacturer A truck, passing results were obtained for all three tests over the Riverside to Hesperia route, all three tests over the Indio to Riverside route, and for one of the three Hesperia to Indio routes. The number of NTE events was greater for the Riverside to Hesperia route, as this route includes a steep uphill climb, with the number of NTE events ranging from 7 to 15. The number of NTE events for the Hesperia to Indio route ranged from 4 to 19 events. The number of NTE events for the Indio to Riverside route ranged from 18 to 27. The NOx emission rates for the valid NTE events of Manufacturer A are provided in Figure 5-2.

Table 5-4 NTE Requirements with Measurement Allowance for Manufacturer A

NTE Requirements with Measurement Allowance						
Route	**Route ID**	**All event**		**Pass event**		**Pass/Fail**
		Numbers	**Duration**	**Numbers**	**Duration**	
CERT-Hes	1	17	1470	15	1346	Pass
	2	7	656	7	656	Pass
	3	13	1494	12	1456	Pass
Hes-Ind	1	19	1234	14	1024	Fail
	2	4	281	4	281	Pass
	3	11	646	10	573	Fail
Ind-CERT	1	27	2707	26	2677	Pass
	2	18	2665	17	2532	Pass
	3	22	2390	22	2390	Pass

Table 5-5 NTE Requirements without Measurement Allowance for Manufacturer A

NTE Requirements WITHOUT Measurement Allowance						
Route	**Route ID**	**All event**		**Pass event**		**Pass/Fail**
		Numbers	**Duration**	**Numbers**	**Duration**	
CERT-Hes	1	17	1470	13	1206	Fail
	2	7	656	6	608	Pass
	3	13	1494	12	1456	Pass
Hes-Ind	1	19	1234	10	794	Fail
	2	4	281	4	281	Pass
	3	11	646	8	443	Fail
Ind-CERT	1	27	2707	26	2677	Pass
	2	18	2665	15	2437	Pass
	3	22	2390	20	2284	Pass

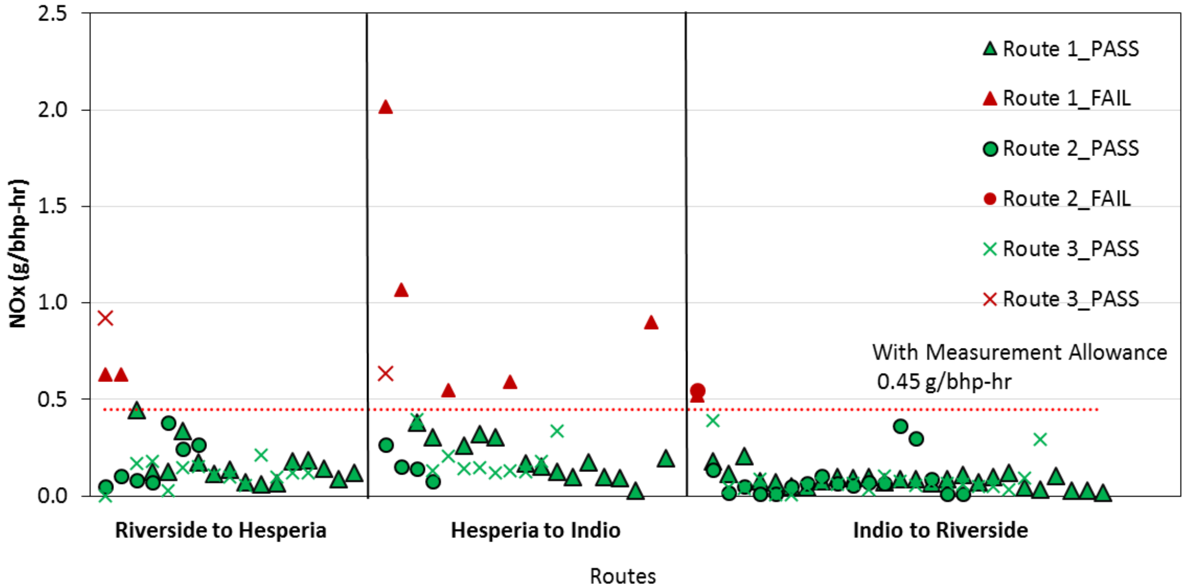


Figure 5-4 NOx emission rates for the valid NTE TEST for Manufacturer A

The activity analysis for the Manufacturer B truck showed similar trends between the different routes. The average speeds for the Riverside to Hesperia, Hesperia to Indio, and Indio to Riverside routes were 38 mph, 51 mph, and 48 mph, respectively. The power levels were also similar to those for the Manufacturer A truck, with cumulative powers of 217 bhp-hr, 247 bhp-hr, and 292 bhp-hr for the Riverside to Hesperia, Hesperia to Indio, and Indio to Riverside routes, respectively. The Manufacturer B truck did have a higher fraction of operation in the NTE zone, however, with the Indio to Riverside route having the highest percentage of activity in the NTE zone (53%), compared to 52% for the Riverside to Hesperia route, and 36% for the Hesperia to Indio route. The Indio to Riverside route had the highest percentage of activity spent in valid NTE events (38%), compared to 34% for the Riverside to Hesperia route, and 15% for the Hesperia to Indio route. The highest emissions were found for the Riverside to Hesperia route (0.49 g/bhp-hr), compared to the Hesperia to Indio route (0.36 g/bhp-hr), followed by the Indio to Riverside route (0.31 g/bhp-hr).

The breakdown of NOx emissions between the NTE and non-NTE operation varied between the different routes. For the Riverside to Hesperia route the highest fraction of NOx was found for the valid NTE events (47.9%), with another 12.9% of the NOx coming from NTE zone operation that did not qualify as an NTE event due to temperature <250°C or the duration being < 30 seconds. Only 7.2% of the NOx was for non-NTE conditions, while 20.7% of the NOx was formed under cold operation conditions.

The Hesperia to Indio route also had nearly half of the NOx emissions coming from valid NTE events (40.9%), with another 29.7% of the NOx coming from NTE zone operation that did not qualify as an NTE event due to temperature <250°C or the duration being < 30 seconds. NOx for non-NTE conditions corresponded to 23.0% of the total, while 10.6% of the NOx was formed under cold operation conditions.

For the Indio to Riverside route, The majority of the NOx was formed during valid NTE events (60.8%), with another 18.4% of the NOx coming from NTE zone operation that did not qualify as an NTE event due to temperature <250°C or the duration being < 30 seconds. Only 8.9% of NOx was formed during non-NTE zone operation and only 11.9% of NOx was formed under cold operation conditions.

Table 5-6 NTE Activity analysis for Manufacturer B (CERT-Hes)

	Route ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	122	4173	32	38	221	0.55		
	2	113	3450	39	37	215	0.52		
	3	86	3017	44	37	214	0.40		
	Ave	107	3547	38	37	217	0.49		
Cold Operation	1	13	398	9	1	8	1.62	10.4	9.5
	2	14	539	14	2	10	1.40	12.8	15.6
	3	33	1299	43	15	76	0.44	38.8	43.1
	Ave	20	745	22	6	31	1.15	20.7	22.7
Non-NTE	1	19	1694	22	10	14	1.34	15.5	40.6
	2	5	805	33	7	5	0.94	4.5	23.3
	3	1	379	43	5	2	0.62	1.6	12.6
	Ave	8	959	33	7	7	0.97	7.2	25.5
Invalid NTE Events, <250C	1	9	233	32	2	20	0.47	7.5	5.6
	2	4	143	26	1	12	0.29	3.1	4.1
	3	1	379	43	5	2	0.62	1.6	12.6
	Ave	5	252	34	3	11	0.46	4.1	7.4
Invalid NTE Events, <30s & >250C	1	11	290	50	4	23	0.49	9.2	6.9
	2	6	269	51	4	20	0.29	5.2	7.8
	3	10	426	55	6	36	0.28	12.0	14.1
	Ave	9	328	52	5	26	0.35	8.8	9.6
Valid NTE Events	1	70	1558	46	20	156	0.45	57.3	37.3
	2	84	1694	48	23	167	0.50	74.4	49.1
	3	10	426	55	6	36	0.28	12.0	14.1
	Ave	55	1226	50	16	120	0.41	47.9	33.5

Table 5-7 NTE Activity analysis for Manufacturer B (Hes-Ind)

	Route ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	96	5459	56	85	221	0.43		
	2	96	7536	47	98	271	0.36		
	3	73	6543	52	94	247	0.29		
	Ave	88	6513	52	92	247	0.36		
Cold Operation	1	15	1363	58	22	50	0.29	15.3	25.0
	2	1	364	55	6	2	0.57	1.1	4.8
	3	11	1177	58	19	34	0.33	15.5	18.0
	Ave	9	968	57	15	29	0.40	10.6	15.9
Non-NTE	1	35	2558	56	40	45	0.78	36.6	46.9
	2	16	4295	41	49	26	0.60	16.3	57.0
	3	12	3029	47	39	28	0.43	16.2	46.3
	Ave	21	3294	48	43	33	0.60	23.0	50.0
Invalid NTE Events, <250C	1	8	292	47	4	22	0.35	8.1	5.3
	2	19	448	47	6	37	0.51	19.7	5.9
	3	12	3029	47	39	28	0.43	16.2	46.3
	Ave	13	1256	47	16	29	0.43	14.7	19.2
Invalid NTE Events, <30s & >250C	1	15	726	59	12	52	0.29	15.6	13.3
	2	19	448	47	6	37	0.51	19.7	5.9
	3	7	1091	59	18	65	0.11	9.6	16.7
	Ave	14	755	55	12	51	0.30	15.0	12.0
Valid NTE Events	1	23	520	50	7	52	0.45	24.4	9.5
	2	50	1379	56	22	137	0.37	52.2	18.3
	3	34	1048	54	16	103	0.33	46.2	16.0
	Ave	36	982	53	15	97	0.38	40.9	14.6

Table 5-8 NTE Activity analysis for Manufacturer B (Ind-CERT)

	Route ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	80	5392	51	76	301	0.27		
	2	109	4853	52	70	281	0.39		
	3	82	6562	42	77	294	0.28		
	Ave	90	5602	48	74	292	0.31		
Cold Operation	1	1	237	54	4	7	0.22	1.8	4.4
	2	34	1213	58	19	74	0.46	31.6	25.0
	3	2	333	56	5	5	0.38	2.3	5.1
	Ave	13	594	56	9	29	0.36	11.9	11.5
Non-NTE	1	6	1786	42	21	13	0.46	7.7	33.1
	2	10	1384	37	14	10	1.02	9.5	28.5
	3	8	2905	25	20	18	0.44	9.6	44.3
	Ave	8	2025	34	18	14	0.64	8.9	35.3
Invalid NTE Events, <250C	1	1	106	58	2	6	0.15	1.2	2.0
	2	5	184	56	3	14	0.39	5.0	3.8
	3	10	225	43	3	20	0.50	12.0	3.4
	Ave	5	172	52	2	13	0.35	6.1	3.1
Invalid NTE Events, <30s & >250C	1	7	558	46	7	43	0.17	9.4	10.3
	2	22	875	57	14	73	0.31	20.5	18.0
	3	6	583	51	8	41	0.14	7.0	8.9
	Ave	12	672	51	10	52	0.21	12.3	12.4
Valid NTE Events	1	64	2705	57	43	231	0.28	79.9	50.2
	2	36	1197	58	19	109	0.33	33.4	24.7
	3	57	2516	59	41	210	0.27	69.0	38.3
	Ave	52	2139	58	35	184	0.29	60.8	37.7

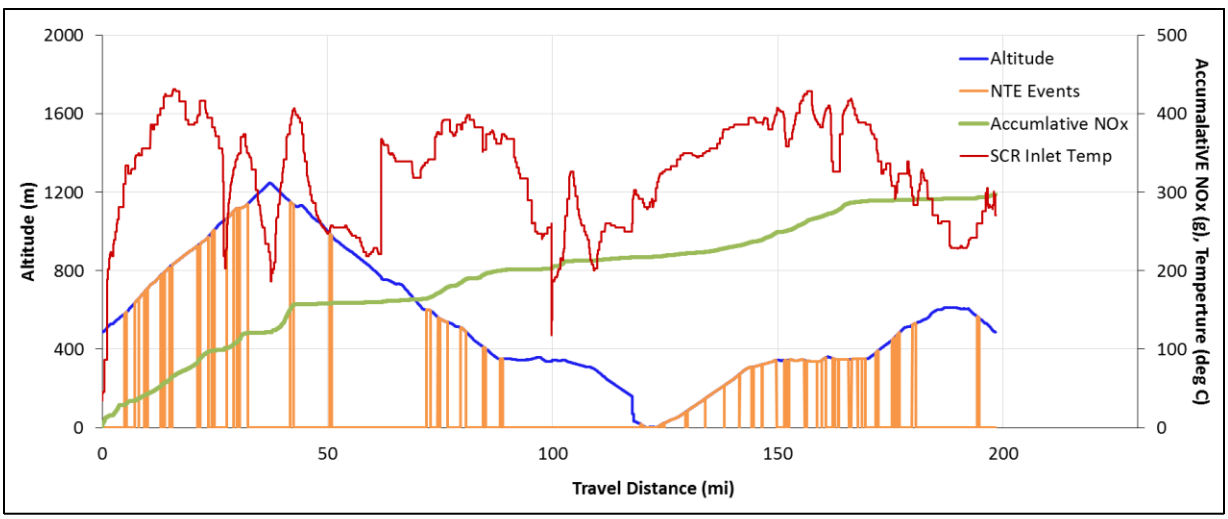


Figure 5-5 Altitude vs NTE event for one test route (Riv-Hes-Indi-Riv) for the Manufacturer B truck

For the Manufacturer B truck, failing NTE results were obtained for all three tests over the Riverside to Hesperia route, for two of the three Hesperia to Indio routes, and one of the three tests over the Indio to Riverside route. The number of NTE events was greater for the Riverside to Hesperia route, as this route includes a steep uphill climb, with the number of NTE events ranging from 8 to 17. The number of NTE events for the Hesperia to Indio route ranged from 11 to 23 events. The number of NTE events for the Indio to Riverside route ranged from 11 to 25. The NOx emission rates for the valid NTE events for the Manufacturer B truck are provided in Figure 5-6.

Table 5-9 NTE Requirements with Measurement Allowance for Manufacturer B

NTE Requirements with Measurement Allowance						
Route	Route ID	All event		Pass event		Pass/Fail
		Numbers	Duration	Numbers	Duration	
CERT-Hes	1	14	1558	5	825	Fail
	2	17	1694	6	371	Fail
	3	8	891	3	420	Fail
Hes-Ind	1	9	520	7	360	Fail
	2	23	1379	16	923	Fail
	3	15	1048	14	955	Pass
Ind-CERT	1	25	2705	23	2509	Pass
	2	11	1197	9	1115	Pass
	3	20	2516	17	2235	Fail

Table 5-10 NTE Requirements without Measurement Allowance for Manufacturer B

NTE Requirements WITHOUT Measurement Allowance						
Route	Route ID	All event		Pass event		Pass/Fail
		Numbers	Duration	Numbers	Duration	
CERT-Hes	1	14	1558	2	183	Fail
	2	17	1694	5	281	Fail
	3	8	891	1	48	Fail
Hes-Ind	1	9	520	3	101	Fail
	2	23	1379	10	508	Fail
	3	15	1048	8	380	Fail
Ind-CERT	1	25	2705	19	1958	Fail
	2	11	1197	5	577	Fail
	3	20	2516	16	2089	Fail

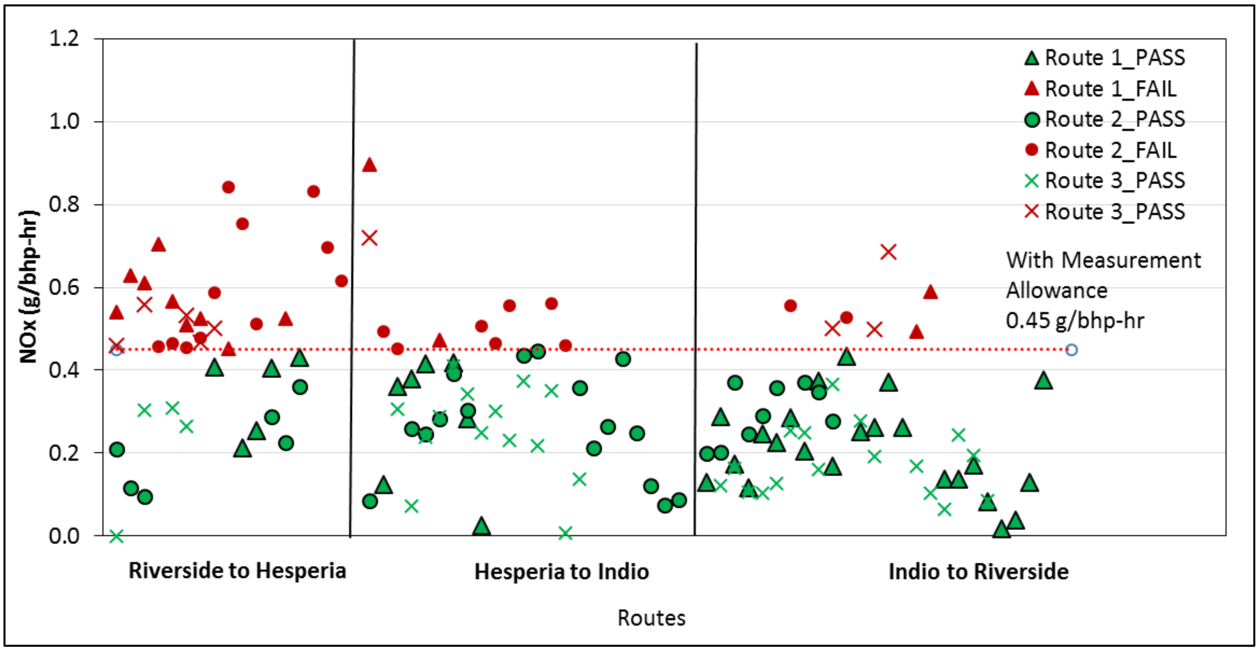


Figure 5-6 NOx emission rates for the valid NTE TEST for Manufacturer B

5.1.1.2 <u>10% Max power and 10% Max Torque</u>

To evaluate the impact of exclusion NTE criteria on the data coverage in the NTE zone, the NTE analysis was repeated with the NTE criteria modified to have exclusions below 10% Max power and 10% Max Torque, as opposed to having all operation below the 30% level for characteristics. Figure 5-7 shows the comparison of activity analysis of standard NTE (30% max power and torque) and modified NTE (10% max power and torque). The activity results are presented in Table 5-11 to Table 5-13 for the Manufacturer A truck and Table 5-14 to Table 5-16 for the Manufacturer B truck.

For the Manufacturer A truck, the modified NTE criteria of 10% max power and 10% max torque increased the fraction of data falling within the NTE zone to 67%, 43% and 64%, respectively, for the Riverside to Hesperia, Hesperia to Indio and Indio to Riverside routes, compared to 52%, 28% and 57% for these routes with the NTE criteria of 30% max power and 30% max torque, respectively. For the Manufacturer B truck, the modified NTE criteria of 10% max power and 10% max torque increased the fraction of data falling within the NTE zone to 53%, 48% and 57%, respectively, for the Riverside to Hesperia, Hesperia to Indio and Indio to Riverside routes, compared to 52%, 43% and 53% for these routes with the NTE criteria of 30% max power and 30% max torque, respectively.

The modified NTE criteria on average increased the amount data within the NTE zone by 12% for the Manufacturer A truck and 6% for the Manufacturer B truck for the three on-road routes of this study.

In terms of valid NTE events, for the Manufacturer A truck, the amount of activity in valid NTE events increased to 40%, 16% and 48% for the Riverside to Hesperia, Hesperia to Indio and Indio to Riverside routes with the modified NTE criteria of 10% max power and 10% max torque, compared to 36%, 10% and 42% for these with the NTE criteria of 30% max power and 30% max torque, respectively. For the Manufacturer B truck, the amount of activity in valid NTE events increased to 41%, 19% and 40% for the Riverside to Hesperia, Hesperia to Indio and Indio to Riverside routes with the modified NTE criteria of 10% max power and 10% max torque, compared to 34%, 15% and 38% for these with the NTE criteria of 30% max power and 30% max torque, respectively. The modified NTE criteria provided on average of 5% and 4% more activity in valid NTE events for the Manufacturer A and Manufacturer B trucks, respectively.

Even though the modified NTE criteria improved data coverage in the NTE zone, no significant change in NOx emission rates was found comparing with those with the original NTE criteria. For the Manufacturer A truck, the NOx emission rates in the NTE zone changed from 0.24 to 0.25 g/bhp-hr for the Riverside to Hesperia route, from 0.39 to 0.40 g/bhp-hr for the Hesperia to Indio route and from 0.18 to 0.19 g/bhp-hr for the Indio to Riverside route. For the Manufacturer B truck, the NOx emission rates in the NTE zone changed from 0.44 to 0.43 g/bhp-hr for the Riverside to Hesperia route, from 0.32 to 0.30 g/bhp-hr for the Hesperia to Indio route and from 0.28 to 0.27 g/bhp-hr for the Indio to Riverside route.

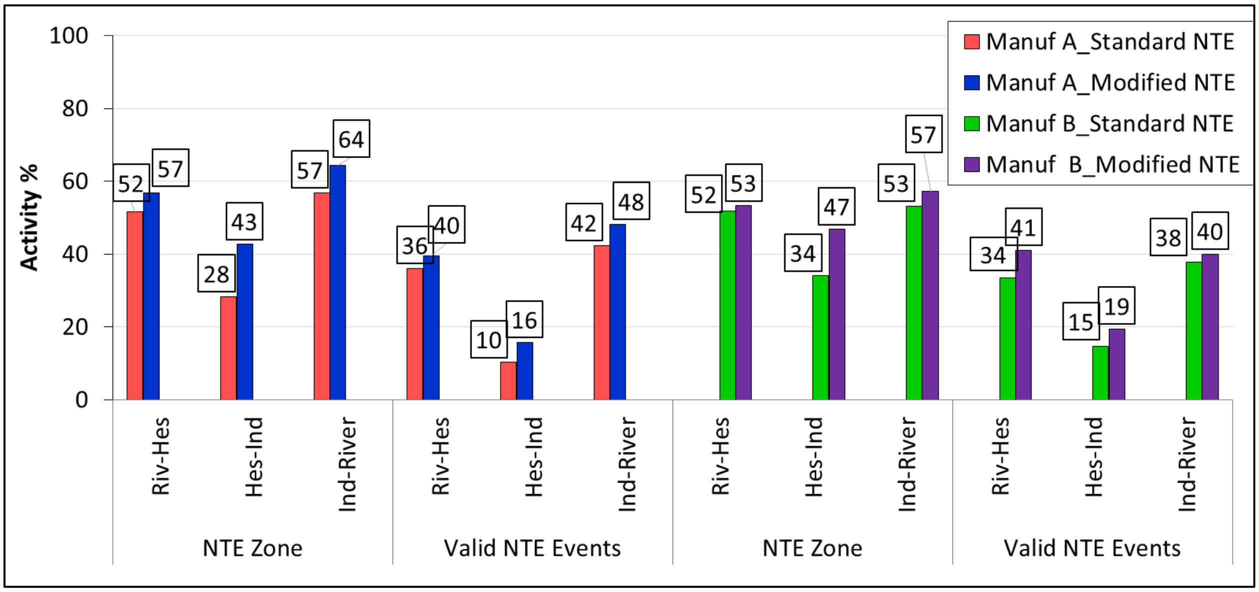


Figure 5-7 Activity Analysis of Standard NTE (30% max power and torque) and Modified NTE (10% max power and torque)

Table 5-11 NTE Activity analysis for Manufacturer A (CERT-Hes) using 10% Power and Torque Criteria

	Route ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	75	3744	34	35	207	0.36		
	2	60	3643	36	37	214	0.28		
	3	50	2923	45	37	199	0.25		
	Ave	62	3437	39	36	207	0.30		
Cold Operation	1	4	67	45	1	7	0.57	5.0	1.8
	2	38	1280	38	13	89	0.43	63.4	35.1
	3	3	95	50	1	9	0.35	6.3	3.3
	Ave	15	481	44	5	35	0.45	24.9	13.4
Non-NTE	1	9	1476	16	6	4	2.34	12.4	39.4
	2	0	888	18	4	1	0.33	0.8	24.4
	3	14	759	34	7	2	7.34	27.7	26.0
	Ave	8	1041	23	6	2	3.34	13.6	29.9
Invalid NTE Events, <250C	1	27	305	22	2	18	1.46	35.4	8.1
	2	1	67	22	0	3	0.39	1.9	1.8
	3	14	232	30	2	14	1.05	28.8	7.9
	Ave	14	201	25	1	12	0.97	22.1	6.0
Invalid NTE Events, <30s & >250C	1	6	274	49	4	21	0.28	7.7	7.3
	2	7	673	47	9	48	0.13	10.9	18.5
	3	2	226	57	4	14	0.12	3.4	7.7
	Ave	5	391	51	5	28	0.18	7.3	11.2
Valid NTE Events	1	30	1622	50	22	158	0.19	39.6	43.3
	2	14	735	48	10	72	0.19	23.0	20.2
	3	17	1611	51	23	160	0.11	33.8	55.1
	Ave	20	1323	50	18	130	0.16	32.1	39.5

Table 5-12 NTE Activity analysis for Manufacturer A (Hes-Indio) using 10% Power and Torque Criteria

	Route ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	128	7161	52	104	239	0.54		
	2	122	6969	54	104	247	0.50		
	3	107	6809	55	103	234	0.46		
	Ave	119	6980	54	104	240	0.50		
Cold Operation	1	25	1080	53	16	19	1.26	19.2	15.1
	2	71	2481	56	39	112	0.64	58.2	35.6
	3	26	1390	57	22	63	0.41	24.1	20.4
	Ave	41	1650	55	26	65	0.77	33.8	23.7
Non-NTE	1	9	2513	50	35	4	1.93	6.7	35.1
	2	7	1962	46	25	5	1.37	6.1	28.2
	3	16	2563	53	38	3	4.86	15.1	37.6
	Ave	11	2346	50	33	4	2.72	9.3	33.6
Invalid NTE Events, <250C	1	43	946	56	15	38	1.14	33.4	13.2
	2	28	871	57	14	33	0.85	22.7	12.5
	3	40	1099	55	17	45	0.89	37.0	16.1
	Ave	37	972	56	15	38	0.96	31.0	13.9
Invalid NTE Events, <30s & >250C	1	12	784	52	11	39	0.30	9.3	10.9
	2	11	1024	56	16	57	0.20	9.1	14.7
	3	9	917	57	15	55	0.17	8.5	13.5
	Ave	11	908	55	14	50	0.22	9.0	13.0
Valid NTE Events	1	40	1838	53	27	138	0.29	31.4	25.7
	2	5	631	58	10	40	0.12	3.9	9.1
	3	16	840	53	12	69	0.24	15.4	12.3
	Ave	20	1103	55	17	82	0.22	16.9	15.7

Table 5-13 NTE Activity analysis for Manufacturer A (Indio-CERT) using 10% Power and Torque Criteria

	Route ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	78	6107	47	80	353	0.22		
	2	91	6608	43	79	306	0.30		
	3	62	5654	50	79	304	0.20		
	Ave	77	6123	47	79	321	0.24		
Cold Operation	1	17	660	59	11	27	0.64	22.0	10.8
	2	11	576	55	9	22	0.53	12.6	8.7
	3	1	49	56	1	2	0.50	1.9	0.9
	Ave	10	428	57	7	17	0.55	12.1	6.8
Non-NTE	1	6	1443	28	11	3	1.62	7.2	23.6
	2	3	2178	26	16	6	0.59	3.8	33.0
	3	6	1711	41	20	3	2.15	10.2	30.3
	Ave	5	1777	32	15	4	1.45	7.1	29.0
Invalid NTE Events, <250C	1	26	464	43	6	26	1.01	33.0	7.6
	2	43	501	39	5	28	1.51	47.3	7.6
	3	28	382	45	5	21	1.31	44.7	6.8
	Ave	32	449	42	5	25	1.27	41.7	7.3
Invalid NTE Events, <30s & >250C	1	7	552	49	7	31	0.24	9.2	9.0
	2	8	391	45	5	24	0.33	8.7	5.9
	3	5	648	50	9	41	0.13	8.8	11.5
	Ave	7	530	48	7	32	0.23	8.9	8.8
Valid NTE Events	1	22	2988	54	45	266	0.08	28.6	48.9
	2	25	2962	54	44	226	0.11	27.6	44.8
	3	21	2864	56	45	236	0.09	34.3	50.7
	Ave	23	2938	55	44	243	0.09	30.2	48.1

Table 5-14 NTE Activity analysis for Manufacturer B (CERT-Hes) using 10% Power and Torque Criteria

	Route ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	122	4173	32	38	221	0.55		
	2	113	3450	39	37	215	0.52		
	3	86	3017	44	37	214	0.40		
	Ave	107	3547	38	37	217	0.49		
Cold Operation	1	13	398	9	1	8	1.62	10.4	9.5
	2	14	539	14	2	10	1.40	12.8	15.6
	3	33	1299	43	15	76	0.44	38.8	43.1
	Ave	20	745	22	6	31	1.15	20.7	22.7
Non-NTE	1	25	1676	23	11	21	1.16	20.4	40.2
	2	5	686	32	6	4	1.45	4.7	19.9
	3	2	360	43	4	4	0.59	2.7	11.9
	Ave	11	907	32	7	10	1.07	9.3	24.0
Invalid NTE Events, <250C	1	9	270	29	2	20	0.44	7.2	6.5
	2	4	189	25	1	13	0.30	3.5	5.5
	3	1	23	42	0	2	0.42	0.9	0.8
	Ave	5	161	32	1	12	0.39	3.9	4.2
Invalid NTE Events, <30s & >250C	1	5	168	49	2	11	0.43	4.1	4.0
	2	2	158	50	2	9	0.25	2.1	4.6
	3	10	461	55	7	36	0.28	11.9	15.3
	Ave	6	262	51	4	19	0.32	6.0	8.0
Valid NTE Events	1	71	1661	47	22	160	0.44	57.8	39.8
	2	87	1878	48	25	179	0.48	76.9	54.4
	3	39	874	41	10	96	0.41	45.7	29.0
	Ave	65	1471	45	19	145	0.44	60.1	41.1

Table 5-15 NTE Activity analysis for Manufacturer B (Hes-Indio) using 10% Power and Torque Criteria

	Route ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	96	5441	56	84	220	0.43		
	2	96	7536	47	98	271	0.36		
	3	73	6543	52	94	247	0.29		
	Ave	88	6507	52	92	246	0.36		
Cold Operation	1	15	1363	58	22	50	0.29	15.3	25.1
	2	1	364	55	6	2	0.57	1.1	4.8
	3	11	1177	58	19	34	0.33	15.5	18.0
	Ave	9	968	57	15	29	0.40	10.6	16.0
Non-NTE	1	30	1734	54	26	25	1.23	31.9	31.9
	2	12	3440	37	36	7	1.69	12.1	45.6
	3	10	2244	43	27	11	0.91	14.0	34.3
	Ave	17	2473	45	29	14	1.27	19.3	37.3
Invalid NTE Events, <250C	1	9	550	51	8	29	0.33	9.8	10.1
	2	21	795	47	10	45	0.47	22.0	10.5
	3	10	297	41	3	19	0.50	13.4	4.5
	Ave	13	547	46	7	31	0.43	15.0	8.4
Invalid NTE Events, <30s & >250C	1	16	1017	60	17	54	0.30	17.1	18.7
	2	10	1394	58	22	73	0.14	10.8	18.5
	3	6	1282	59	21	57	0.10	7.7	19.6
	Ave	11	1231	59	20	61	0.18	11.8	18.9
Valid NTE Events	1	25	777	54	12	63	0.40	26.0	14.3
	2	52	1543	57	24	145	0.36	54.1	20.5
	3	36	1543	56	24	125	0.29	49.5	23.6
	Ave	38	1288	56	20	111	0.35	43.2	19.4

Table 5-16 NTE Activity analysis for Manufacturer B (Indio-CE-CERT) using 10% Power and Torque Criteria

	Route ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	80	5392	51	76	301	0.27		
	2	109	4853	52	70	281	0.39		
	3	82	6562	42	77	294	0.28		
	Ave	90	5602	48	74	292	0.31		
Cold Operation	1	1	237	54	4	7	0.22	1.8	4.4
	2	34	1213	58	19	74	0.46	31.6	25.0
	3	2	333	56	5	5	0.38	2.3	5.1
	Ave	13	594	56	9	29	0.36	11.9	11.5
Non-NTE	1	10	1640	40	18	19	0.56	13.1	30.4
	2	9	1176	33	11	7	1.36	8.7	24.2
	3	8	2590	22	16	13	0.60	9.6	39.5
	Ave	9	1802	31	15	13	0.84	10.5	31.4
Invalid NTE Events, <250C	1	1	194	60	3	8	0.10	1.0	3.6
	2	6	258	58	4	16	0.41	5.9	5.3
	3	10	281	40	3	21	0.50	12.6	4.3
	Ave	6	244	52	3	15	0.33	6.5	4.4
Invalid NTE Events, <30s & >250C	1	9	621	46	8	44	0.19	10.7	11.5
	2	20	855	57	13	65	0.31	18.6	17.6
	3	4	590	48	8	33	0.14	5.4	9.0
	Ave	11	689	50	10	47	0.21	11.6	12.7
Valid NTE Events	1	59	2700	58	43	224	0.26	73.4	50.1
	2	38	1351	58	22	118	0.32	35.2	27.8
	3	58	2768	59	46	223	0.26	70.1	42.2
	Ave	51	2273	59	37	188	0.28	59.6	40.0

5.1.2 Chassis Dynamometer Testing

NTE analyses were conducted separately for the different chassis dynamometer driving cycles, including the cold start UDDS, UDDS, Transient, Cruise and high-speed Cruise cycles. Summaries of the activity statistics for these test cycles are provided in Table 5-17 to Table 5-21 for the Manufacturer A Truck and Table 5-24 to Table 5-28 for the Manufacturer B truck. The results of the basic NTE emissions analyses are provided in Table 5-22 and Table 5-23, respectively, for the Manufacturer A truck and in Table 5-29 and Table 5-30, respectively, for the Manufacturer B truck. In each case, the data were evaluated with the application of the NTE measurement allowance and without the measurement allowance.

The activity analysis for the Manufacturer A truck showed the high-speed cruise cycles had the highest percentage of activity in the NTE zone (72%), compared to 47 % for the cruise cycle, and less than 30% for UDDS and transient cycles. The Cold start UDDS only had 6% activity falling in NTE zone with over 66% eliminated due to the cold operation. The high-speed cruise also had the highest percentage of activity spent in valid NTE events (63%), compared to 24% for the cruise cycle, and less than 4 % for other cycles.

The breakdown of NOx emissions between the NTE and non-NTE operation varied between the different cycles. For the high-speed cruise, the highest fraction of NOx was found for the valid NTE events (58%), with another 34% of the NOx coming from NTE zone operation that did not qualify as a valid NTE event due to temperature <250°C or the duration being < 30 seconds, with only 7.7% of NOx emissions found during non-NTE operation.

The cruise cycle showed a relatively high fraction of NOx generated during valid NTE events (30%), with another 53% of the NOx coming from NTE zone operation that did not qualify as an NTE event due to temperature <250°C or the duration being < 30 seconds. Still, only 17.3% of NOx was formed for operation outside the NTE zone.

Lower fractions of NOx were generated during valid NTE events for the urban cycles (UDDS and transient), which was consistent with the NTE data exclusion of transient and low load operation data. For the UDDS cycle, only 7% NOx was generated during valid NTE events, with another 75% of the NOx coming from operation in the NTE zone that was excluded (temperature <250°C or the duration being < 30 seconds). The transient cycle had zero NOx from the valid NTE events, but 80% of NOx came from operation in the NTE zone.

For the Cold start UDDS, over 97% NOx was generated during the cold start operation and less than 2% from the NTE zone.

Table 5-17 NTE Activity analysis for Manufacturer A over the CS-UDDS cycle

	Cycle ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	21	1051	18	5	25	0.86		
	2	24	1062	19	6	26	0.91		
	3	37	1009	19	5	26	1.42		
	Ave	27	1041	19	5	26	1.06		
Cold Operation	1	20	607	16	3	17	1.17	95.2	57.8
	2	23	712	20	4	21	1.09	98.4	67.0
	3	36	746	20	4	23	1.59	98.2	73.9
	Ave	26	688	19	4	20	1.28	97.2	66.2
Non-NTE	1	0	338	13	1	2	0.19	1.7	32.2
	2	0	300	12	1	2	0.10	0.9	28.2
	3	0	233	15	1	2	0.20	0.8	23.1
	Ave	0	290	13	1	2	0.16	1.1	27.8
Invalid NTE Events, <250C	1	0	0	-	-	0	-	0.0	0.0
	2	0	0	-	-	0	-	0.0	0.0
	3	0	0	-	-	0	-	0.0	0.0
	Ave	0	0			0		0.0	0.0
Invalid NTE Events, <30s & >250C	1	1	106	45	1	6	0.12	3.1	10.1
	2	0	50	40	1	3	0.07	0.7	4.7
	3	0	30	33	0	2	0.22	1.0	3.0
	Ave	0	62	40	1	3	0.13	1.6	5.9
Valid NTE Events	1	0	0	-	-	0	-	0.0	0.0
	2	0	0	-	-	0	-	0.0	0.0
	3	0	0	-	-	0	-	0.0	0.0
	Ave	0	0			0		0.0	0.0

Table 5-18 NTE Activity analysis for Manufacturer A over the UDDS cycle

	Cycle ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	17	1062	19	6	23	0.74		
	2	22	1014	20	6	23	0.93		
	3	20	989	21	6	22	0.88		
	Ave	19	1022	20	6	23	0.85		
Non-NTE	1	5	777	12	3	5	1.01	27.3	73.2
	2	5	727	12	2	5	1.16	24.6	71.7
	3	5	724	15	3	5	0.99	24.7	73.2
	Ave	5	743	13	3	5	1.05	25.6	72.7
Invalid NTE Events, <250C	1	6	100	26	1	6	0.89	33.3	9.4
	2	9	109	27	1	8	1.16	42.8	10.7
	3	5	86	26	1	6	0.88	24.5	8.7
	Ave	7	98	26	1	7	0.98	33.5	9.6
Invalid NTE Events, <30s & >250C	1	6	153	45	2	10	0.55	33.5	14.4
	2	5	143	43	2	8	0.62	24.2	14.1
	3	9	144	40	2	10	0.88	44.0	14.6
	Ave	7	147	43	2	10	0.68	33.9	14.4
Valid NTE Events	1	1	32	52	0	2	0.63	5.9	3.0
	2	2	35	56	1	2	0.80	8.4	3.5
	3	1	35	57	1	2	0.64	6.7	3.5
	Ave	1	34	55	1	2	0.69	7.0	3.3

Table 5-19 NTE Activity analysis for Manufacturer A over the Transient cycle

	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	28	1968	15	8	40	0.70		
Non-NTE	6	1572	11	5	10	0.56	20.3	79.9
Invalid NTE Events, <250C	10	168	27	1	13	0.77	36.6	8.5
Invalid NTE Events, <30s & >250C	12	228	29	2	17	0.73	43.0	11.6
Valid NTE Events	0	0	-	-	0	-	0.0	0.0

Table 5-20 NTE Activity analysis for Manufacturer A over the Cruise cycle

	Cycle ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	8	2077	40	23	64	0.12		
	2	3	1903	43	23	62	0.06		
	3	4	1819	45	23	62	0.07		
	Ave	5	1933	43	23	62	0.08		
Non-NTE	1	1	1131	28	9	14	0.07	13.2	54.5
	2	1	893	32	8	12	0.05	18.8	46.9
	3	1	1027	40	11	17	0.05	19.8	56.5
	Ave	1	1017	33	9	14	0.06	17.3	52.6
Invalid NTE Events, <250C	1	2	23	40	0	2	0.69	21.3	1.1
	2	0	0	-	-	0	-	0.0	0.0
	3	1	34	40	0	3	0.48	34.0	1.9
	Ave	1	19	40	0	2	0.58	18.4	1.0
Invalid NTE Events, <30s & >250C	1	2	390	52	6	21	0.12	30.8	18.8
	2	1	354	50	5	20	0.07	40.8	18.6
	3	1	511	52	7	27	0.05	31.6	28.1
	Ave	2	418	52	6	23	0.08	34.4	21.8
Valid NTE Events	1	3	533	55	8	26	0.11	34.7	25.7
	2	1	656	55	10	30	0.05	40.4	34.5
	3	1	247	55	4	14	0.04	14.6	13.6
	Ave	2	479	55	7	23	0.07	29.9	24.6

Table 5-21 NTE Activity analysis for Manufacturer A over the Hi-speed Cruise cycle

	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	32	2246	50	31	111	0.29		
Non-NTE	2	634	23	4	5	0.55	7.7	28.2
Invalid NTE Events, <250C	0	0	-	-	0	-	0.0	0.0
Invalid NTE Events, <30s & >250C	11	204	35	2	19	0.57	34.3	9.1
Valid NTE Events	19	1408	64	25	87	0.21	58.0	62.7

For the Manufacturer A truck, passing results were obtained for all cruise and high-speed cruise cycles, except for one cruise cycle using the without measurement allowance condition. Even though it failed the NTE criteria all three UDDS cycles, only one NTE event was generated during all three cycles and NTE approach wasn't designed to evaluate the emissions during the transient operation. The average number of NTE events was 7 for both cruise and high-speed cruise cycles.

Table 5-22 NTE Requirements with Measurement Allowance for Manufacturer A

NTE Requirements with Measurement Allowance						
Cycle	Cycle ID	All event		Pass event		Pass/Fail
		Numbers	Duration	Numbers	Duration	
CS-UDDS	1	0	0	0	0	-
	2	0	0	0	0	-
	3	0	0	0	0	-
UDDS	1	1	32	0	0	Fail
	2	1	35	0	0	Fail
	3	1	35	0	0	Fail
Cruise	1	9	533	9	533	Pass
	2	13	656	13	656	Pass
	3	7	247	7	247	Pass
Transient × 3		0	0	0	0	-
Hi Speed Cruise × 3		7	1408	6	1342	Pass

Table 5-23 NTE Requirements without Measurement Allowance for Manufacturer A

NTE Requirements WITHOUT Measurement Allowance						
Cycle	Cycle ID	All event		Pass event		Pass/Fail
		Numbers	Duration	Numbers	Duration	
CS-UDDS	1	0	0	0	0	-
	2	0	0	0	0	-
	3	0	0	0	0	-
UDDS	1	1	32	0	0	Fail
	2	1	35	0	0	Fail
	3	1	35	0	0	Fail
Cruise	1	9	533	8	468	Fail
	2	13	656	13	656	Pass
	3	7	247	7	247	Pass
Transient × 3		0	0	0	0	-
Hi Speed Cruise × 3		7	1408	6	1342	Pass

The activity analysis for the Manufacturer B truck showed the high-speed cruise cycles had the highest percentage of activity in the NTE zone (61%), compared to 30 % for the cruise cycle, and less than 26% for UDDS and transient cycles. The Cold start UDDS only had 18% activity falling in NTE zone, with 48% excluded due to cold start operation. The high-speed cruise also had the highest percentage of activity spent in valid NTE events (37%), compared to 5% for the cruise cycle, and zero for other cycles.

The breakdown of NOx emissions between the NTE and non-NTE operation varied between the different cycles. For the high-speed cruise, the highest fraction of NOx was found for the valid NTE events (43%), with another 41% of the NOx coming from NTE zone operation that did not qualify as a valid NTE event due to temperature <250°C or the duration being < 30 seconds, with only 15% of NOx emissions found during non-NTE operation.

The cruise cycle showed a relatively high fraction of NOx generated during valid NTE events (8%), with another 47% of the NOx coming from NTE zone operation that did not qualify as an NTE event due to temperature <250°C or the duration being < 30 seconds. Over 45% of NOx was formed for operation outside the NTE zone.

Lower fractions of NOx were generated during valid NTE events for the urban cycles (UDDS and transient), which was consistent with the NTE data exclusion of transient and low load operation data. For the UDDS cycle, zero NOx was generated during valid NTE events, with another 57% of the NOx coming from operation in the NTE zone that was excluded (temperature <250°C or the duration being < 30 seconds). The transient cycle also had zero NOx from the valid NTE events, but 70% of NOx came from operation in the NTE exclusion zone.

For the Cold start UDDS, over 67% NOx was generated during the cold start operation and 23% from the NTE zone.

Table 5-24 NTE Activity analysis for Manufacturer B over the CS-UDDS cycle

	Cycle ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	24	1060	19	6	25	0.98		
	2	22	1025	19	5	23	0.95		
	Ave	23	1043	19	5	24	0.97		
Cold Operation	1	13	426	8	1	8	1.70	55.0	40.2
	2	18	567	13	2	13	1.41	82.9	55.3
	Ave	16	497	11	2	10	1.55	68.9	47.8
Non-NTE	1	3	410	18	2	2	1.09	10.7	38.7
	2	1	307	18	2	2	0.67	5.0	30.0
	Ave	2	359	18	2	2	0.88	7.9	34.3
Invalid NTE Events, <250C	1	7	140	41	2	9	0.74	27.9	13.2
	2	2	112	49	2	6	0.39	10.6	10.9
	Ave	5	126	45	2	8	0.56	19.2	12.1
Invalid NTE Events, <30s & >250C	1	2	84	41	1	5	0.30	6.4	7.9
	2	0	39	30	0	3	0.13	1.5	3.8
	Ave	1	62	35	1	4	0.21	4.0	5.9
Valid NTE Events	1	0	0	-	-	0	-	0.0	0.0
	2	0	0	-	-	0	-	0.0	0.0
	Ave	0	0			0		0.0	0.0

Table 5-25 NTE Activity analysis for Manufacturer B over the UDDS cycle

	Cycle ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	10	1012	20	6	21	0.46		
	2	8	1014	20	6	20	0.41		
	3	9	1025	20	6	21	0.45		
	Ave	9	1017	20	6	21	0.44		
Non-NTE	1	3	748	14	3	4	0.79	34.7	73.9
	2	4	764	14	3	4	1.08	49.0	75.3
	3	4	774	14	3	4	0.90	41.5	75.5
	Ave	4	762	14	3	4	0.92	41.7	74.9
Invalid NTE Events, <250C	1	2	124	32	1	8	0.25	21.1	12.3
	2	3	128	31	1	9	0.30	32.6	12.6
	3	4	162	31	1	11	0.41	47.6	15.8
	Ave	3	138	31	1	9	0.32	33.8	13.6
Invalid NTE Events, <30s & >250C	1	4	140	42	2	9	0.50	44.1	13.8
	2	1	121	43	1	7	0.18	15.8	11.9
	3	1	89	44	1	6	0.18	10.9	8.7
	Ave	2	117	43	1	7	0.29	23.6	11.5
Valid NTE Events	1	0	0	-	-	0	-	0.0	0.0
	2	0	0	-	-	0	-	0.0	0.0
	3	0	0	-	-	0	-	0.0	0.0
	Ave	0	0			0		0.0	0.0

Table 5-26 NTE Activity analysis for Manufacturer B over the Transient cycle

	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	9	1969	15	8	37	0.25		
Non-NTE	3	1563	12	5	8	0.34	30.1	79.4
Invalid NTE Events, <250C	4	166	21	1	13	0.32	42.3	8.4
Invalid NTE Events, <30s & >250C	3	240	29	2	16	0.16	27.7	12.2
Valid NTE Events	0	0	-	-	0	-	0.0	0.0

Table 5-27 NTE Activity analysis for Manufacturer B over the Cruise cycle

	Cycle ID	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	1	21	2084	40	23	53	0.40		
	2	16	1918	43	23	54	0.29		
	3	13	1970	42	23	54	0.24		
	Ave	17	1991	42	23	54	0.31		
Non-NTE	1	11	1571	36	16	24	0.45	51.4	75.4
	2	7	1362	40	15	24	0.31	47.0	71.0
	3	5	1271	37	13	17	0.27	36.6	64.5
	Ave	8	1401	38	15	22	0.34	45.0	70.3
Invalid NTE Events, <250C	1	0	0	-	-	0	-	0.0	0.0
	2	1	69	37	1	5	0.29	9.4	3.6
	3	2	78	38	1	6	0.35	15.6	4.0
	Ave	1	49	37	1	4	0.32	8.3	2.5
Invalid NTE Events, <30s & >250C	1	10	478	52	7	27	0.35	45.3	22.9
	2	6	394	54	6	21	0.27	36.3	20.5
	3	4	452	52	7	21	0.21	34.8	22.9
	Ave	7	441	53	6	23	0.28	38.8	22.1
Valid NTE Events	1	1	35	57	1	2	0.35	3.3	1.7
	2	1	93	57	1	4	0.27	7.3	4.8
	3	2	169	56	3	9	0.18	13.0	8.6
	Ave	1	99	57	2	5	0.27	7.9	5.0

Table 5-28 NTE Activity analysis for Manufacturer B over the Hi-speed Cruise cycle

	NOx g	Activity seconds	Avg Speed mph	Distance mile	Power bhp-hr	NOx g/bhp-hr	NOx %	Activity %
Total	28	2233	50	31	93	0.30		
Non-NTE	4	863	35	8	10	0.42	15.4	38.6
Invalid NTE Events, <250C	3	98	42	1	9	0.35	11.8	4.4
Invalid NTE Events, <30s & >250C	8	450	55	7	29	0.28	29.4	20.2
Valid NTE Events	12	822	65	15	45	0.27	43.4	36.8

For the Manufacturer B truck, passing results were obtained for all cruise and high-speed cruise cycles with the measurement allowance. Only one cruise cycle passed the NTE criteria without the measurement allowance. There was no NTE events for all the UDDS and Transient cycles and NTE approach wasn't designed to evaluate the emissions during the transient operation. The average number of NTE events was 15 for high-speed cruise cycle and a lower number (3) was observed for the cruise cycle.

Table 5-29 NTE Requirements with Measurement Allowance for Manufacturer B

NTE Requirements with Measurement Allowance						
Cycle	Cycle ID	All event		Pass event		Pass/Fail
		Numbers	Duration	Numbers	Duration	
CS-UDDS	1	0	0	0	0	-
	2	0	0	0	0	-
UDDS	1	0	0	0	0	-
	2	0	0	0	0	-
	3	0	0	0	0	-
Cruise	1	1	35	1	35	Pass
	2	2	93	2	93	Pass
	3	4	169	4	169	Pass
Transient × 3		0	0	0	0	-
Hi Speed Cruise × 3		15	822	14	789	Pass

Table 5-30 NTE Requirements without Measurement Allowance for Manufacturer B

NTE Requirements WITHOUT Measurement Allowance						
Cycle	Cycle ID	All event		Pass event		Pass/Fail
		Numbers	Duration	Numbers	Duration	
CS-UDDS	1	0	0	0	0	-
	2	0	0	0	0	-
UDDS	1	0	0	0	0	-
	2	0	0	0	0	-
	3	0	0	0	0	-
Cruise	1	1	35	0	0	Fail
	2	2	93	1	53	Fail
	3	4	169	4	169	Pass
Transient × 3		0	0	0	0	-
Hi Speed Cruise × 3		15	822	13	708	Fail

5.2 Moving Average Window (MAW) Analysis

The focus of this subsection is on the analysis of the on-road testing results using the MAW method. As discussed in section 2.1.3.2, the MAW method defines a continuous series of windows based on the amount of work that is generated during the certification test. In this case, the work from the FTP cycle is used as the basis for determining the MAW work windows. For valid windows, average power is required to be at least 10% of max engine power, and at least 50% of the windows should be valid for a given test run to be considered valid. The MAW method also does not include an exclusion requiring the aftertreatment temperatures to be above 250°C. For emissions, the pass fail criteria for the MAW method is that 90% of the windows should have emissions less than 1.5 times the certification limit. It should be noted that the MAW method was not applied to the chassis dynamometer testing results because the MAW method requires windows of work that exceed those of the FTP engine test. Thus, only the Cruise cycle had sufficient work to apply the MAW window.

5.2.1 Without temperature criteria

The average NOx emission rates of passed windows and failed windows are provided in Figure 5-8 for the Manufacturer A and B trucks. The results for the MAW analysis for the Manufacturer A Truck are presented in 5-31 for the activity analyses and in Table 5-32 for the emissions in comparison with the MAW criteria. The results for the MAW analysis for the Manufacturer B Truck are presented in 5-33 for the activity analyses and in Table 5-34 for the emissions in comparison with the MAW criteria. Figure 5-9 and Figure 5-10 show the window conformity factor of one test route for the Manufacturer A and Manufacturer B trucks, respectively.

Figure 5-8 shows that NOx emissions for failing windows were significantly higher than those of passing windows. The NOx emissions of passing windows for the Manufacturer A truck were lower compared to those for the Manufacturer B trucks, while the NOx emissions of failing windows for the Manufacturer A truck were higher.

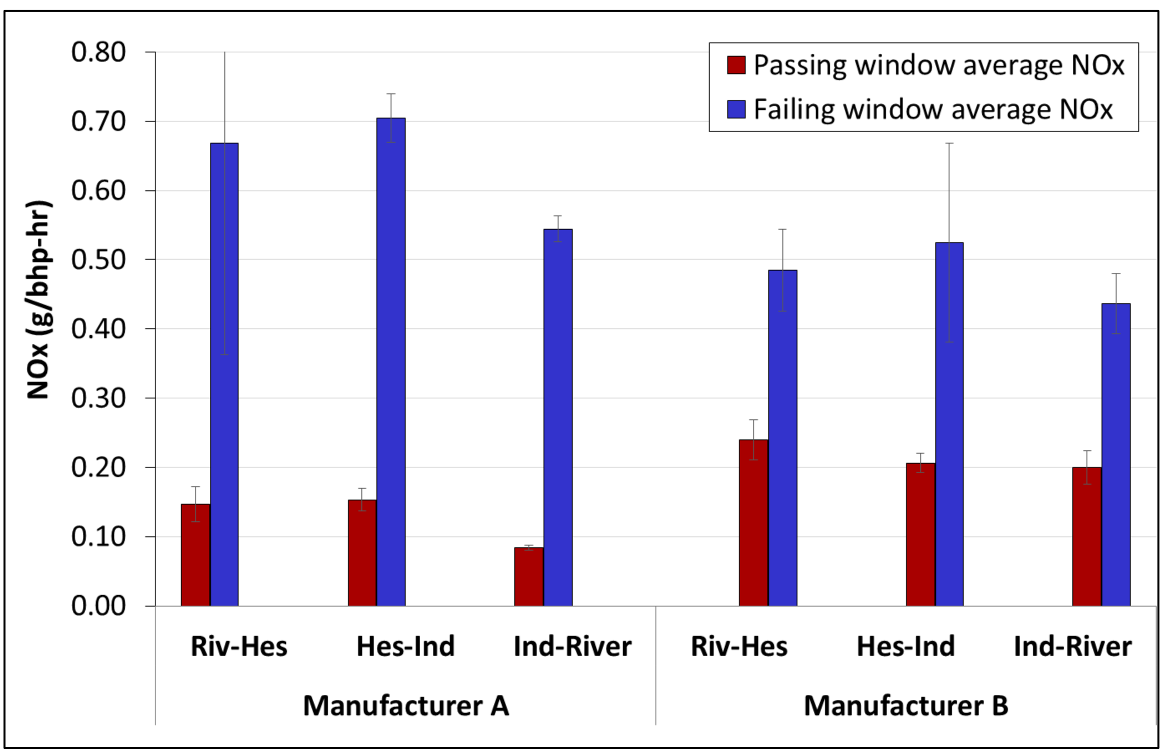


Figure 5-8 Average NOx emission rates of passed windows and failed windows

The activity results in terms of average speed are similar to those presented above, with the average speed for the Hesperia to Indio and Indio to Riverside routes being comparable, while the lowest average speed was seen for the Riverside to Hesperia route. Both the Hesperia to Indio and Indio to Riverside routes also had greater than 76% of the driving at speeds higher than 47 mph, whereas only 46% of the driving on the Riverside to Hesperia route was at greater than 47 mph. The Hesperia to Indio route, had a very small fraction of the driving <31 mph (7%) compared to Riverside to Hesperia and Indio to Riverside routes, which had 30% and 18%, respectively, of the driving below 31 mph.

Table 5-31 MAW Activity analysis for Manufacturer A

Speed	Route ID	CE-CERT-Hep		Hes-Ind		Ind -CE-CERT	
		Activity %	MAW Req. Trip Comp (%)	Activity %	MAW Req. Trip Comp (%)	Activity %	MAW Req. Trip Comp (%)
<= 50 km/hr (31mph)	1	38	20	7	20	18	20
	2	35	20	10	20	23	20
	3	17	20	5	20	14	20
	Ave	30	20	7	20	18	20
<= 75 km/hr (47mph)	1	22	25	8	25	5	25
	2	23	25	7	25	6	25
	3	26	25	5	25	6	25
	Ave	24	25	7	25	6	25
> 75 km/hr	1	40	55	85	55	77	55
	2	42	55	83	55	71	55
	3	58	55	90	55	80	55
	Ave	46	55	86	55	76	55
Average speed (mph)	1	34		52		47	
	2	36		54		43	
	3	45		55		50	
	Ave	39		54		47	
Work over in-use (bhp-hr)	1	207		239		353	
	2	214		247		306	
	3	199		234		304	
	Ave	207		240		321	
Work ratio (in-use/FTP-certification)	1	8		9		13	
	2	8		9		11	
	3	7		9		11	
	Ave	8		9		12	

An evaluation for the Manufacturer A truck on-road emissions data in terms of the MAW requirements is presented in Table 5-32. For this analysis, the MAW requirements were based on the work from a typical FTP test. For the MAW methodology, several criteria are utilized to determine if the test is acceptable. For the windows calculated over the course of the route, at least 50% should be valid MAW windows, which requires that the average power should be at least 10% of the maximum power. For the on-road testing, all the routes had a 100% of valid windows.

For the emissions, the pass fail criteria is then based on what percentage of windows have average emissions that are less than 1.5 times the conformity factor or standard. The passing criteria for the MAW requirement is then that 90% of the windows should have emissions less than 1.5 times the conformity factor. For the Manufacturer A truck, the emissions were found to fail the MAW test for a majority of the routes, with only two tests for the Riverside to Hesperia passing. For the Riverside to Hesperia route, between 79.3 and 91.6% of the windows passed the 1.5 times criteria, compared to 64.0 to 77.3% of the windows for the Indio to Riverside route, and 35.8 to 41.7% of the routes for the Hesperia to Indio route.

Table 5-32 MAW Requirements for Manufacturer A

Work-Based MAW													
Route	Route ID	All MAW Windows	Window Avg Nox g/bhp-hr	MAW Valid (>20%Pmax) Windows	Window Avg g/bhp-hr	MAW Invalid Windows	Window Avg Nox g/bhp-hr	MAW Valid (%) Windows	Window Avg g/bhp-hr	CF Total	CF <= 1.5	CF <=1.5 (%)	Pass/Fail
CERT-Hes	1	2984	0.244	2984	0.244	-		100	Valid Test	2984	2367	79.3	Fail
	2	2911	0.186	2911	0.186	-		100	Valid Test	2911	2667	91.6	Pass
	3	2287	0.181	2287	0.210	-		100	Valid Test	2287	2125	92.9	Pass
Hes-Ind	1	6801	0.497	6801	0.497	-		100	Valid Test	6801	2432	35.8	Fail
	2	6563	0.505	6563	0.505	-		100	Valid Test	6563	2735	41.7	Fail
	3	6316	0.482	6316	0.482	-		100	Valid Test	6316	2305	36.5	Fail
Ind-CERT	1	5597	0.244	5597	0.244	-		100	Valid Test	5597	3582	64.0	Fail
	2	6048	0.260	6048	0.260	-		100	Valid Test	6048	3814	63.1	Fail
	3	5088	0.179	5088	0.179	-		100	Valid Test	5088	3721	73.1	Fail

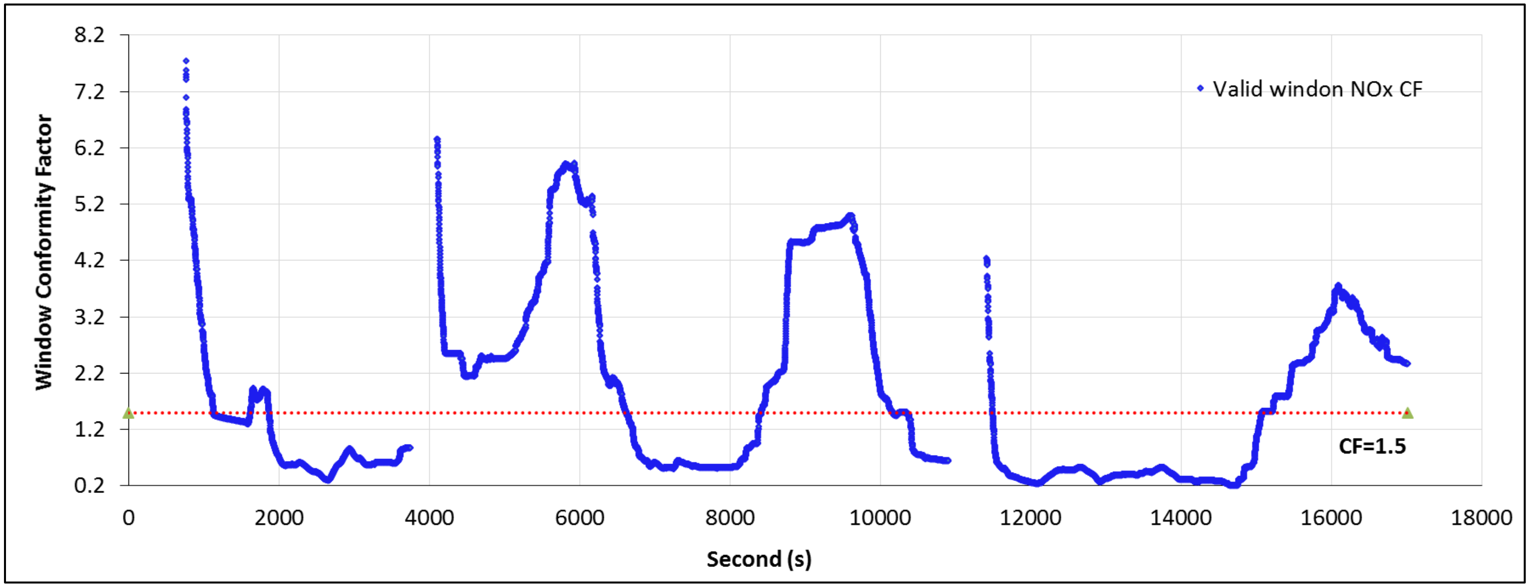


Figure 5-9 Window conformity factor for one test route (Riv-Hes-Indi-Riv) for the Manufacturer A truck

The results for the MAW analysis for the Manufacturer B Truck are presented in Table 5-33 for the activity analyses and in Table 5-34 for the emissions for the Manufacturer B truck in comparison with the MAW criteria.

The activity results in terms of average speed are similar to those presented above, with the average speed for the Hesperia to Indio and Indio to Riverside routes being comparable, while the lowest average speed was seen for the Riverside to Hesperia route. Both the Hesperia to Indio and Indio to Riverside routes also had greater than 77% of the driving at speeds higher than 47 mph, whereas only 40% of the driving on the Riverside to Hesperia route was at greater than 47 mph. The fraction of activity <31 mph varied from 27% for the Riverside to Hesperia route to 18% for the Indio to Riverside route to 13% for the Hesperia to Indio route.

Table 5-33 MAW Activity analysis for Manufacturer B

Speed	Route ID	CE-CERT-Hep Activity %	CE-CERT-Hep MAW Req. Trip Comp (%)	Hes-Ind Activity %	Hes-Ind MAW Req. Trip Comp (%)	Ind -CE-CERT Activity %	Ind -CE-CERT MAW Req. Trip Comp (%)
<= 50 km/hr (31mph)	1	38	20	4	20	13	20
	2	29	20	23	20	12	20
	3	14	20	12	20	30	20
	Ave	27	20	13	20	18	20
<= 75 km/hr (47mph)	1	26	25	10	25	4	25
	2	29	20	4	25	3	25
	3	30	25	3	25	5	25
	Ave	28	23	6	25	4	25
> 75 km/hr	1	36	55	87	55	82	55
	2	29	20	73	55	84	55
	3	56	55	85	55	65	55
	Ave	40	43	81	55	77	55
Average speed (mph)	1	32		56		51	
	2	39		47		52	
	3	44		52			
	Ave	38		52		51	
Work over in-use (bhp-hr)	1	221		221		301	
	2	215		271		281	
	3	214		247		294	
	Ave	217		246		292	
Work ratio (in-use/FTP-certification)	1	8		8		11	
	2	8		10		10	
	3	8		9		11	
	Ave	8		9		11	

An evaluation for the Manufacturer B truck on-road emissions data in terms of the MAW requirements is presented in Table 5-33. For the on-road testing, all the routes had a 100% of valid windows.

In terms of passing/failing the MAW test, the Manufacturer B truck was found to have failed the MAW test for all the tests on each test route. The highest percent of MAW windows <1.5 times the conformity factor was for the Indio to Riverside route, with a range from 44.1 to 79.9%. The Hesperia to Indio route had between 21.8 and 54.7% of the windows being <1.5 times the conformity limit. The Riverside to Hesperia route showed the lowest percentage, with only 6.2 to 25.8% of the windows being <1.5 times the conformity limit.

Table 5-34 MAW Requirements for Manufacturer B

Work-Based MAW													
Route	Route ID	All MAW		MAW Valid (>20%Pmax)		MAW Invalid		MAW Valid (%)		CF Total	CF <= 1.5	CF <=1.5 (%)	Pass/Fail
		Windows	Window Avg Nox g/bhp-hr	Windows	Window Avg Nox g/bhp-hr	Windows	Window Avg Nox g/bhp-hr	Windows	Window Avg Nox g/bhp-hr				
CERT-Hes	1	3311	0.471	3311	0.471	-		100	Valid Test	3311	206	6.2	Fail
	2	2383	0.489	2383	0.489	-		100	Valid Test	2383	385	16.2	Fail
	3	2343	0.379	2343	0.379	-		100	Valid Test	2343	604	25.8	Fail
Hes-Ind	1	4994	0.588	4994	0.588	-		100	Valid Test	4994	1091	21.8	Fail
	2	7062	0.351	7062	0.351	-		100	Valid Test	7062	2553	36.2	Fail
	3	6049	0.310	6049	0.310	-		100	Valid Test	6049	3306	54.7	Fail
Ind-CERT	1	4922	0.228	4626	0.234	-		100	Valid Test	4626	3436	74.3	Fail
	2	4395	0.363	4395	0.363	-		100	Valid Test	4395	1937	44.1	Fail
	3	5802	0.248	5802	0.248	-		100	Valid Test	5802	4638	79.9	Fail

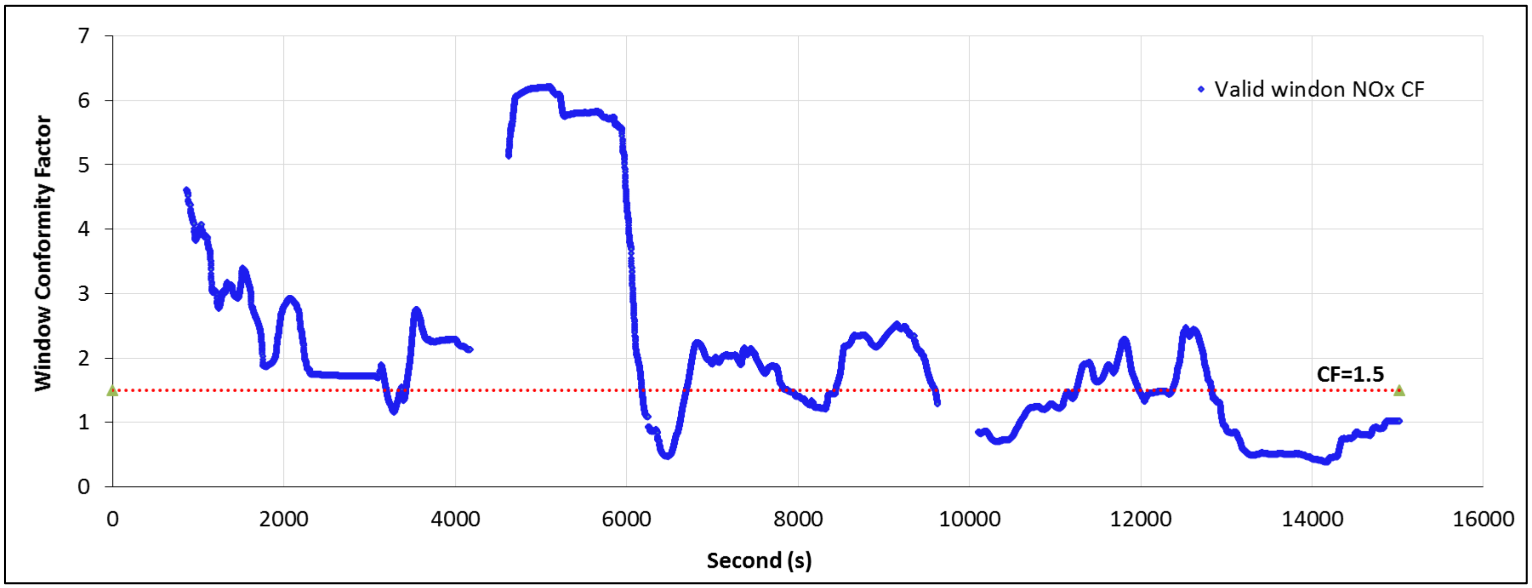


Figure 5-10 Window conformity factor for one test route (Riv-Hes-Indi-Riv) for the Manufacturer B truck

5.2.2 *With temperature criteria*

The NTE criteria excludes test data where the SCR temperature is lower than 250˚C, as NOx conversion efficiencies are relatively low at these lower temperatures. However, the MAW method does not have such a temperature criteria. Figure 5-11 presents shows the conformity factors and average SCR temperatures for one test route of both trucks. The results showed that a large number of windows with CFs higher than 1.5 had average SCR temperatures lower than 250˚C for the Manufacturer A truck, while only a small fraction of windows for the Manufacturer B truck had SCR temperatures below 250˚C. This is consistent with the fact that the average SCR temperatures for Manufacturer B were higher than those for Manufacturer A for all the on-road routes.

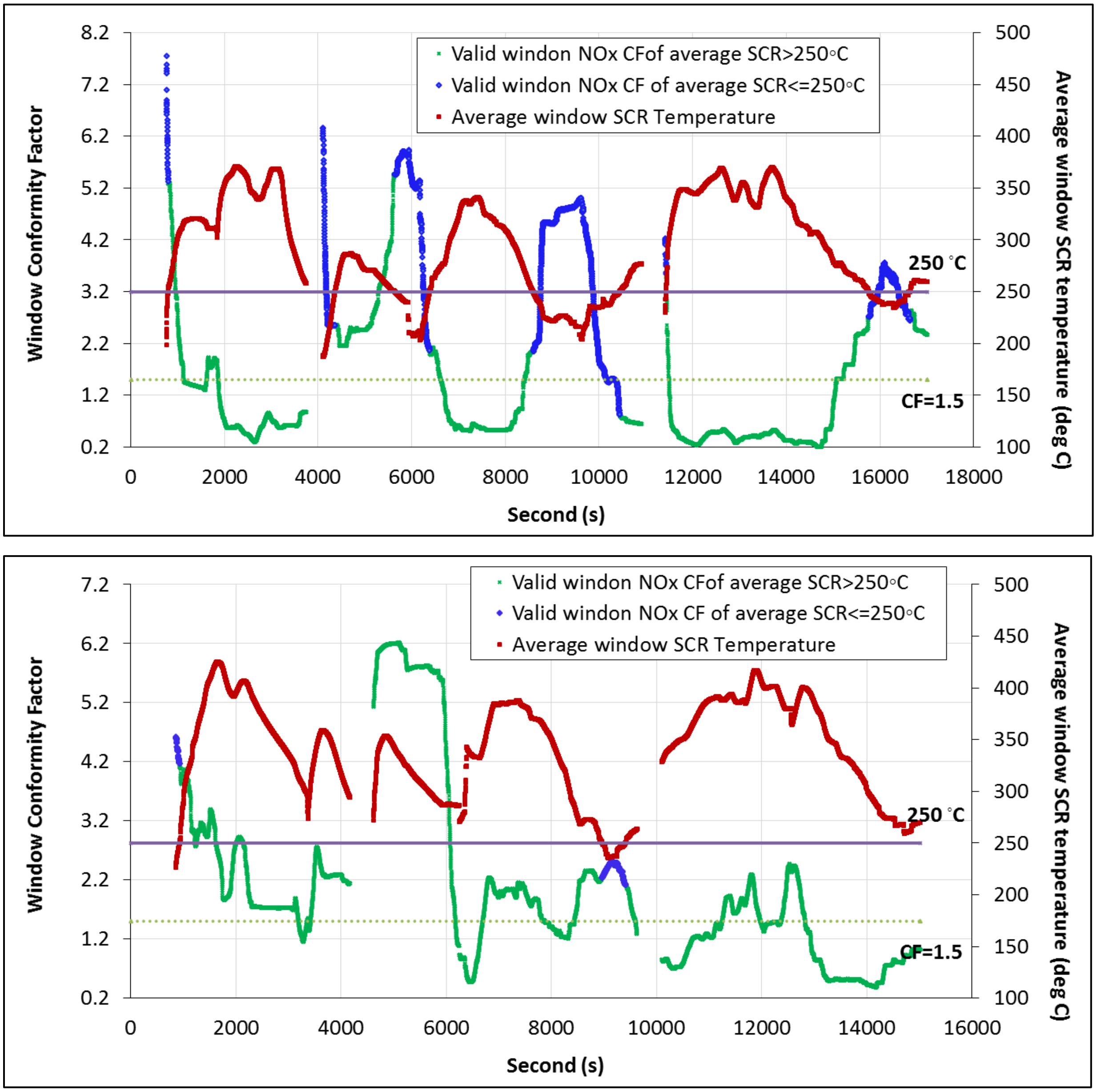


Figure 5-11 Window conformity factor vs average window SCR temperature for one test route (Riv-Hes-Indi-Riv) for the Manufacturer A truck (Top) and Manufacturer B (Bottom)

Further analysis of the impacts of adding a temperature criteria requiring the average window SCR temperature to be higher than 250˚C was conducted for the MAW method. This analysis was only conducted for the Manufacturer A truck, as only a small fraction of windows for the Manufacturer

B truck had average window SCR temperatures lower than 250°C. The comparison of MAW analysis without and with temperature criteria for the Manufacturer A truck is provided in Table 5-35. Although the overall pass rate didn't change by eliminating data points with low SCR efficiency operation, the fraction of CF less than 1.5 increased 14% for the Hesperia to Indio route and 10% for the Indio to Riverside route. The coverage of valid windows decreased after applying the temperature criteria, but the overall coverage was still higher than 59% for all routes.

Table 5-35 Comparison of MAW analysis without and with temperature criteria for the Manufacturer A Truck

Manufacturer A											
Route	Route ID	Valid Windows		Valid Window Avg NOx (g/bhp-hr)		MAW Valid (%)		CF <=1.5 (%)		Pass/Fail	
		Standard	Modified	Standard	Modified	Standard	Modified	Standard	Modified	Standard	Modified
CERT-Hes	1	2984	2947	0.24	0.23	100	99	79.3	80.3	Fail	Fail
	2	2911	2847	0.19	0.18	100	98	91.6	93.7	Pass	Pass
	3	2287	2225	0.18	0.16	100	97	92.9	95.8	Pass	Pass
	Ave	2727	2673	0.20	0.19	100	98	88.0	89.9		
Hes-Ind	1	6801	3860	0.50	0.29	100	57	35.8	56.7	Fail	Fail
	2	6563	3823	0.51	0.28	100	58	41.7	63.3	Fail	Fail
	3	6316	3968	0.48	0.24	100	63	57.9	57.9	Fail	Fail
	Ave	6560	3884	0.49	0.27	100	59	45.1	59.3		
Ind-CERT	1	5597	4690	0.24	0.17	100	84	64.0	76.4	Fail	Fail
	2	6048	5332	0.26	0.20	100	88	63.1	71.5	Fail	Fail
	3	5088	4343	0.18	0.14	100	85	77.3	85.7	Fail	Fail
	Ave	5578	4788.33	0.23	0.17	100	86	68.1	77.9		

5.3 Comparisons with other recent studies

The results of the NTE and MAW analyses can be compared to other studies of heavy-duty in-use emissions. CARB is in the process of conducting in-use testing for a range of different manufacturers. To date, CARB has tested approximately 23 vehicles (O'Cain, 2018). The routes used for the CARB test are very similar to those used in our study, in that the CARB route goes from El Monte to Hesperia to Indio and then back to El Monte. Similar to the results of our study, the CARB testing is showing that a large fraction of the operation over this route is not in the NTE zone or do not represent valid NTE events. In earlier results from this work, Tu et al. (2016) showed approximately 16 percent of operation being in the NTE zone and typically 9 percent of operation being the valid NTE events over the route. This is lower than the average of 47% of three routes of two vehicles in our study. The few fraction of NTE events for the CARB study is due in part to the extra distance for the CARB routes between El Monte to Riverside where there are few NTE events.

In terms of emissions results for the three engine families tested, O'Cain et al. (2018) found 6 of 10 vehicles to be noncompliant with the NTE for one engine family, with an average NTE emission rate of 0.59 g/bhp-hr, and 8 of 10 vehicles to be noncompliant for the second engine family, with an average NTE emission rate of 1.02 g/bhp-hr. The percentage of failing NTE events was 60% and 80%, respectively, for these two manufacturers. To date, the first three engine from the third family were found to pass, so the third engine family is currently in compliance with the in-use emissions limits. The passing ratio over the 9 tests per vehicle in our study was 7/9 for the Manufacturer A truck and 3/9 for the Manufacturer B truck. The NOx emission rates for the valid NTE events of our study were 0.18 g/bhp-hr for the Manufacturer A truck and 0.41 for the Manufacturer B truck, which were lower than the values above.

Bartholome et al. (2018) of CARB conducted some more extensive analysis of manufacturer derived HDIUC data. They found that only 5% of this data was valid NTE events, and that 24% of the tests did not have any valid NTE events. For the valid NTE events, 90.8% of the data was found to pass the NTE criteria. They modified different exclusion criteria for valid NTE operation, including changing torque from 30% to 10% Max torque, changing power from 30% to 10% Max power, and deleting some temperature criteria. With the modified NTE criteria, they found that the percent of operation within valid NTEs increased to 28%, that the fraction of tests with no valid NTE events decreased to only 3.4%, and that the fraction of passing NTE events decreased to 71%. The modification of the NTE criteria in the Bartholome et al. study showed greater impact than observed in the present study, where modifying the NTE criteria to 10% of maximum power and torque only increased the fraction of valid NTEs by less than 5%. They also evaluated this data with the MAW method and found that the MAW method captures more of test time and emissions during real-world operation compared with both the current and modified NTE method. With the MAW criteria, they found that the percent of operation within valid NTEs increased to 60%, that 62% of the total trip NOx was included in the analysis, and that the fraction of passing NTE events decreased to 11.6%. In terms of the MAW method, the activity analysis of this study did show a significant improvement in the amount of data coverage, as 100% of activity was in a valid window for both Manufacturer A and the Manufacturer B trucks. However, the fail rate was high for both vehicles.

The differences between the percentage of passing NTEs between the actual manufacturer data and the testing by CARB and our results could be due to differences in the types of operation between the different types of testing. For the in-use testing, the manufacturers merely need to identify vehicles that are conducting typical operation. This operation has generally shown a relatively small percentage of operation in the NTE.

5.4 Potential Improvements for Heavy-Duty In-Use Compliance Testing Procedures

CARB is currently evaluating potential alternatives to the present In-Use compliance testing. The main issue with the current NTE procedure is that the NTE procedure excludes a large percentage of operation. As the original NTE procedures were targeted more for long haul operation, the criteria in terms of power levels excludes a considerable fraction of lower load operation. The requirement for NTE event durations of at least 30 seconds also excludes a large amount of operation.

Improvements to the in-use compliance procedures have focused primarily on developing methodologies to cover a wider range of operation, and to ensure that areas of operation where disproportionate amounts of NOx are formed are also covered. As discussed above, Bartolome et al. found that the fraction of operation covered during in-use testing could be increased from 5% for NTE operation to 28% by broadening the NTE criteria and to 60% using a MAW method. Correspondingly, the percent of NOx generated during testing increased from 6% for the NTE operation to 33% by broadening the NTE criteria and to 62% using a MAW method.

The results of our testing show similarly that the use of a MAW methodology would increase the percentage of operation covered as part of an in-use testing procedure. For the Manufacturer A truck, the percentage of operation covered by the NTE procedure represented approximately 45% with an average emission rate of 0.27 g/bhp-hr. The operation excluded by the NTE represented approximately 16% of the emissions at a typical emissions rate of 0.94 g/bhp-hr. Similarly for the Manufacturer B truck, the percentage of operation covered by the NTE procedure represented approximately 46% with an average emission rate of 0.34 g/bhp-hr. The operation excluded by the NTE represented approximately 13% of the emissions at a typical emissions rate of 0.74 g/bhp-hr. For the MAW analysis, the percentage of operation included increased to 85% for the Manufacturer A truck and 92% for the Manufacturer B truck. The average emission rate for the operation in the MAW was 0.23 g/bhp-hr for the Manufacturer A truck and 0.37 g/bhp-hr for the

Manufacturer B truck, while the average emission rate for operation outside of the MAW was 0.74 g/bhp-hr for the Manufacturer A truck and 0.43 g/bhp-hr for the Manufacturer B truck.

There were also limitations for the MAW procedure in terms of data coverage. Even though 100% of the activity in our study was in valid MAW control areas, this was due to the freeway driving conditions. For other normal daytime traffic conditions, Yoon et al. (2016) found only about 50% of the MAWs were valid. The NOx emission rates of the invalid MAW areas were found to generate more NOx emission than those of the valid MAWs. The data coverage could also be even worse during the urban low-power truck operations.

6 Summary and Conclusions

The State of California has a number of regions that are out of compliance with national air quality standards for both ozone and particulate matter (PM) emissions. Although considerable progress has been made in reducing the contributions of vehicle emissions to the emissions inventory and in improving air quality, further reductions in oxides of nitrogen (NOx) emissions are still needed to achieve future air quality goals in California. In an effort to reduce emissions from heavy-duty diesel vehicles (HDDVs), regulatory agencies have tightened laboratory certification limits and have implemented not-to-exceed (NTE) in-use testing requirements. While significant steps have been taken to reduce NOx emissions from HDDVs, it is still uncertain how effective these changes have been in reducing in-use NOx emissions. The goal of this study was to evaluate the effectiveness of current HDDE certification and HDDV in-use compliance procedures for controlling in-use NOx emissions from HDDVs and to suggest possible changes to these procedures that could facilitate California in meeting ambient air quality standards for ozone and PM.

Two 2010-compliant heavy-duty diesel engines (HDDEs) equipped with diesel particulate filter (DPF) and selective catalytic reduction (SCR) technologies and from different manufacturers were tested for emissions using an engine-dynamometer, a chassis-dynamometer, and on-road. The engines included a 2014 model year (MY) engine from Manufacturer A and a 2013 MY engine from Manufacturer B, both equipped in their own truck chassis. Emissions testing for this study included initial chassis-dynamometer testing, on-road testing, an engine-dynamometer test conducted with the engine removed from the truck chassis, and then final chassis-dynamometer testing to provide a comparison with the initial chassis test conducted prior to removing the engine.

6.1 Literature Review

6.1.1 Relevant Emissions Studies

A literature review was conducted to better understand the types of methods that are used to characterize emissions from heavy-duty vehicles, and to understand the NOx emissions rates of in-use heavy-duty diesel vehicles with these methodologies. A variety of techniques used to evaluate in-use emissions of heavy-duty diesel vehicles were reviewed, including chassis dynamometer testing, on-road PEMS testing, and other techniques such as remote sensing devices (RSD), probe-based methodologies, tent-like systems such as the On-Road Heavy-Duty Emissions Measurement System (OHMS), and the Portable Emissions AcQuisition System (PEAQS). Chassis dynamometer results have shown that NOx emissions vary considerably from cycle to cycle and for different vehicles/engines. NOx emissions are lowest for higher speed cruise cycles where the higher exhaust temperatures provide more optimal SCR performance. More moderate cycles, such as the Urban Dynamometer Driving Schedule (UDDS), tend to show higher emissions. The emissions from more moderate cycles are often higher than the typical certification values when characterized on a g/bhp-hr basis, which can be due to a number of different factors, including the temperature of the SCR aftertreatment system and differences in the load level and profile of the cycle compared to the certification test. The on-road results from several PEMS studies have also shown that NOx emissions for different types of driving can often be higher than certification NOx levels and that disproportionately higher NOx emissions are generated under lower load operating conditions. Studies of NTE operation have also shown that a large fraction of in-use operation does not meet the criteria for a valid NTE events, in terms of operating within the NTE zone for a period of at least 30 seconds with the aftertreatment system temperature above 250°C. Results from roadside measurement methods designed to survey a larger number of vehicles, including RSD, probe-based methodologies, OHMS, and PEAQS, have also shown that there is an important fraction of high emitting trucks that contribute a disproportionate amount of NOx.

6.1.2 Vehicle and Engine Testing

The results of the vehicle and engine testing conducted as part of this study are summarized below. Table ES-1 provides a summary of test cycles for the different test conditions. For discussion purposes, the test cycles were separated into urban (UDDS, FTP, and HHDDT Transient) and freeway or steady state (HHDDT Cruise, HHDDT-S, and RMC) driving conditions. The engine dynamometer version of the UDDSs for each engine was developed from the engine operation recorded during the chassis dynamometer UDDS cycle. The on-road test route went from the CE-CERT facility to Hesperia, from Hesperia to Indio, and then from Indio returning to the CE-CERT facility. Cold start UDDS and FTP tests were also conducted for the chassis dynamometer and engine dynamometer testing, respectively. Testing included engine activity and concurrent emission measurements with a PEMS and CE-CERT's MEL, with the exception of the on-road testing, where only PEMS were used.

6.2 Emissions Testing and Results

6.2.1 Results

6.2.1.1 NOx emissions

In general, the results showed that the results for the urban testing were higher than those for the freeway type of driving, which can be attributed to lower SCR operating temperatures throughout the cycle that reduce the effectiveness of the SCR in reducing engine out NOx. A summary of the findings for NOx emissions for the urban cycles is as follows:

- Over all of the urban test conditions, the Manufacturer A truck showed NOx emissions in a range of 0.28 to 0.91 g/bhp-hr, while those for the Manufacturer B truck showed a similar emissions range, with emissions ranging from 0.16 to 1.05 g/bhp-hr.
- The highest emissions were found for the CS-UDDS and regular UDDS on the chassis dynamometer for the Manufacturer A truck (0.72 to 0.91 g/bhp-hr), and for the CS-UDDS, CS-FTP, and engine dynamometer transient cycles for the Manufacturer B truck (0.68 to 1.05).
- The lowest emissions were found for the engine dynamometer UDDS (eUDDS) and FTP cycles for the Manufacturer A truck (approximately 0.3 g/bhp-hr) and for the on-road and initial chassis dynamometer transient cycles for the Manufacturer B truck (approximately 0.2 g/bhp-hr).
- For the Manufacturer A truck, the transient, CS-FTP and on-road UDDS results were in the middle of the other results, ranging from about 0.43 to 0.61 g/bhp-hr. For the Manufacturer B truck, the initial chassis dynamometer UDDS, the engine dynamometer UDDS, the final chassis dynamometer UDDS, the FTP, and the final chassis dynamometer transient results were in the middle of the other results, ranging from about 0.28 to 0.41 g/bhp-hr.
- Interestingly, NOx emissions for weighted FTP (1/7×Cold_FTP +6/7×Hot_FTP) cycle were above the certification level of 0.20 g/bhp-hr for both engines, with values of 0.34 and 0.45 g/bhp-hr for the Manufacturer A and Manufacturer B engines, respectively.

The results for the cruise/RMC tests were generally lower than those for the urban cycles. A summary of the findings for NOx emissions for the cruise/RMC cycles is as follows:

- For the Manufacturer A truck, the cruise results were on the order of 0.10 g/bhp-hr, while the high-speed cruise results were 0.30 g/bhp-hr or less. For the Manufacturer B truck, the cruise and high speed cruise results were on the order of 0.30 g/bhp-hr or less.
- The on-road testing results were higher for the both trucks, ranging from 0.22 to 0.50 g/bhp-hr for the Manufacturer A truck and from 0.35 to 0.49 g/bhp-hr for the Manufacturer B truck, with the highest emissions for the Hesperia to Indio test route for the Manufacturer A truck and for the Riverside to Hesperia test route for the Manufacturer B truck. Note that the Hesperia test route is uphill driving and needs higher load on the engine, which could cause the higher emissions for that test route. While the Hesperia to Indio route includes considerable downhill driving, where the load on the engine is relatively low, which could be contributing to the higher emissions for that test route segment on a g/bhp-hr basis.

In comparing the results for the different test cycles between the different testing conditions (i.e., chassis dynamometer, on-road, and engine dynamometer), the results showed mixed trends, depending on the vehicle and test cycle for the urban driving cycles. A summary of the findings is as follows:

- The Manufacturer A truck for the UDDS showed the highest emissions for the chassis dynamometer testing, followed by the on-road testing, with the lowest UDDS emissions for the engine dynamometer testing. Discussions with Manufacturer A suggested that the engine could have been operating in a cold start mode during the engine dynamometer testing due in part to an absence of vehicle dashboard cluster communication, which potentially caused the engine to operate with retarded fuel injection timing. This explanation needs to be further evaluated; however, with a deeper investigation of the emission control related ECU parameters along with engine laboratory test conditions
- The Manufacturer B truck also showed the highest UDDS results for the chassis dynamometer testing, with comparable results for the on-road and engine dynamometer UDDS results for the urban driving cycles. For the Manufacturer B truck/engine, the higher emissions for the chassis dynamometer were attributed to lower SCR temperatures and corresponding lower SCR NOx reduction efficiencies.
- Interestingly, for Manufacturer B, the transient test results showed higher emissions for the engine dynamometer testing compared to the chassis dynamometer tests, which could be attributed to the lower SCR temperatures for the engine dynamometer tests.
- The freeway/RMC testing results were more consistent between the different testing conditions. Both trucks showed consistent emissions between different testing conditions (i.e., chassis dynamometer, on-road, and engine dynamometer), except for the hi-speed cruise for the Manufacturer A truck and the cruise for the Manufacturer B truck.
- The on-road testing results were higher for both trucks, compared with the cruise and hi-speed cruise cycles for the chassis dynamometer and engine dynamometer testing.

SCR temperature is an important measure of how effectively the SCR can remove NOx emissions, with temperatures above 250°C generally needed for the SCR to reach its full effectiveness. A summary of the findings for the SCR temperature is as follows:

- For Manufacturer A, most of the hot start cycles had average SCR inlet temperatures above 250°C, except for the UDDS cycle for the final chassis dynamometer tests, on-road UDDS and the transient cycles for the engine dynamometer and the final chassis dynamometer tests. For Manufacturer B, only the hot start UDDS cycles of the initial chassis dynamometer had average SCR temperatures above 250°C, with a range of 199 to 248°C for the other hot start urban cycles.

- Although the average SCR temperatures for different cycles were often above 250°C, SCR temperatures would still also vary between different parts of the cycle for different, which did lead to differences in NOx emissions between the different types of testing methods that were used in this study.
- The average SCR inlet temperatures were at or above 250°C for the Cruise, HHDDT-S cycles, on-road driving cycles, and RMC cycles of the engine dynamometer testing for both vehicles.
- The average SCR inlet temperatures for the cold start cycles were lower than those for the hot start cycles with a range from 217 to 240°C for Manufacturer A and from 165 to 182°C for Manufacturer B.

The efficiency of the SCR system in removing NOx was another important characteristic in understanding the different between different tests and different test methods. The cycle average SCR efficiencies for the Manufacturer A and Manufacturer B trucks ranged from 68 to 98%. A summary of the findings for the performance of SCR is as follows:

- For the Manufacture A truck, the SCR efficiencies for the cruise and hi-speed cruise cycles were higher than those for the urban driving cycles. For the Manufacturer B truck, the SCR efficiencies for the cruise and hi-speed cruise cycles were comparable to those for the urban driving cycles.
- The SCR efficiencies were found to be a function of the SCR inlet temperature for both vehicles. For inlet SCR temperatures higher than 250◦C, the SCR conversion efficiencies remained consistently high (>80%). At temperatures below 250◦C, the SCR efficiencies were generally lower, although this varied from cycle to cycle.
- The SCR efficiencies were also found to vary as a function of engine load, especially for the Manufacturer B truck. The highest SCR efficiencies (>90%) were observed between 30 to 60% load for the Manufacturer A truck and between 10 to 40% load for the Manufacturer B truck.

6.2.1.2 Other emissions

PM, CO and THC mass emissions were low for most of the test cycles. A summary of the findings for PM, CO and THC emissions is as follows:

- Average PM emissions were below 0.01 g/bhp-hr for both vehicles and nearly all tests.
- On a g/bhp-hr basis, CO emissions were up to 1.76 /bhp-hr for the urban cycles but were lower for the highway cycles, with all being below 0.13 /bhp-hr. This is considerably below the 15.5 g/bhp-hr standard.
- THC emissions were higher for the urban test cycles, where all tests were below 0.046 g/bhp-hr, than the cruise/highway conditions, where all tests were below 0.007 g/bhp-hr. The highest emissions were seen for the cold start tests, including the CS_UDDS and CS_FTP.

6.3 NTE and MAW Analyses

6.3.1 NTE Analyses

The on-road NOx emissions results were evaluated based on the standard NTE criteria, which include various exclusions, such as operation where the power and torque are below 30% of maximum and where the aftertreatment temperature is below 250°C, and a requirement that the event duration is at least 30 seconds in durations. Additional analyses were also conducted where the criteria were modified to only exclude operation where the power and torque are below 10% of maximum. The results using the modified criteria were similar to those for the standard criteria, and they are discussed in greater detail in the main report. For 2010 and newer trucks, the passing criteria for the NTE test is that at least 90% of time-weighted NTE pass events should be below a threshold 0.45 g/bhp-hr for NOx, based on 1.5 times the certification standard + 0.15 g/bhp-hr (for a PEMS accuracy margin). NTE analyses were conducted separately for the triplicate tests over the three main on-road driving segments, including the Riverside to Hesperia, Hesperia to Indio, and Indio to Riverside routes, as the different routes were not necessarily conducted as a continuous sequence over the course of a single day.

The NTE analysis results are summarized in this section, including the number of valid NTE events and passing NTE events, the percentage of the total trip time in the NTE zone and in valid NTEs, and the percentage of total trip NOx emitted in the NTE zone and during valid NTE events.

- Over the test routes, the percentage of activity in the NTE zone ranged from 21.9 to 65.4% for the Manufacturer A truck and from 28.2 to 62.5% for the Manufacturer B truck.
- A smaller percentage of the activity also met the criteria for a valid NTE event, i.e., including requirements for having a duration of at least 30 seconds and an aftertreatment temperature > 250°C, ranging from 4.0 to 51.1% for the Manufacturer A truck and from 9.5 to 50.2% for the Manufacturer B truck. These activity fractions are higher than those that have been observed by CARB during its testing over the same routes, where NTE zone operation represented approximately 16% of operation and valid NTE events represented approximately 9% of operation. Note the CARB routes were longer comparing with our study due to the distance between El Monte to Riverside, where relatively few NTE events are generated.
- Over all routes, the Manufacturer A truck passed the NTE criteria for 7 of 9 tests, while the Manufacturer B truck passed for only 3 of 9 tests.
- Over the full test routes, a majority of the NOx was generated under operating conditions in the NTE zone (from 28.7 to 90.5% of NOx for the two trucks), while a much lower percentage of NOx was generated under conditions that met all the criteria for a valid NTE event (from 2.9 to 79.9% of NOx for the two trucks)..
- Average emissions for passing NTE events ranged from 0.09 to 0.24 g/bhp-hr for the Manufacturer A truck and from 0.29 to 0.41 g/bhp-hr for the Manufacturer B truck, while failing NTE events ranged from 0.71 to 1.12 g/bhp-hr and 0.72 to 0.83 g/bhp-hr, respectively, for the two trucks.
- NOx emissions for operation outside the NTE zone were significantly higher compared to those in the NTE zone for both vehicles. NOx emission rates during passing NTE events were lower than those for overall activity in the NTE zone and for the whole trip for the Manufacturer A truck.
- NOx emission rates for valid NTE events were comparable to those of overall activity in the NTE zone, but were lower than the values for the whole trip for the Manufacturer B truck.

6.3.2 MAW Analyses

The moving averaging window (MAW) method defines a continuous series of windows based on the amount of work done by the engine when it is certified on an engine dynamometer. In this case, that work is based on the results from the FTP engine dynamometer tests. For valid windows, average power is required to be at least 10% of max engine power, and at least 50% of the windows should be valid for a given test run to be considered valid. The MAW method also does not include an exclusion requiring the aftertreatment temperatures to be above 250◦C. For emissions, the pass fail criteria for the MAW method is that 90% of the windows should have emissions less than 1.5 times the certification limit, which is generally termed the conformity factor (CF). The measurement allowance that is used to account for potential PEMS inaccuracies for the NTE method is not included in the MAW method. As such, the MAW method is more stringent in terms of have less data exclusion, as well as a lower emissions threshold.

The results of the MAW analyses are shown in this section:

- The activity analysis of this study showed a significant improvement of the amount of data that that met the MAW criteria compared with that for the NTE criteria.
- The emissions were found to fail the MAW test for a majority of the routes. Only two tests for the Riverside to Hesperia route passed for the Manufacturer A truck, while the Manufacturer B truck failed the MAW test for all the tests on each test route.
- The fraction of operation passing the MAW criteria for the Manufacturer A truck ranged from 36 to 93%, with most tests higher than 63%. The fraction of operation passing the MAW criteria for the Manufacturer B truck ranged from 6 to 80%, with half of tests below 36%.
- Since the NTE criteria excludes test data where the SCR temperature is lower than 250◦C, as NOx conversion efficiencies are relatively low at these lower temperatures, the MAW method was evaluated with this temperature criteria added for the Manufacturer A truck. Although the overall pass rate didn't change by eliminating data points with low SCR efficiency operation, the fraction of operation below the emission threshold of 1.5 times the certification standard increased 14% for the Hesperia to Indio route and 10% for the Indio to Riverside route. The coverage of valid windows decreased after applying the temperature criteria, but the overall coverage was still higher than 59%.
- Average emissions for pass MAW windows ranged from 0.08 to 0.15 g/bhp-h for the Manufacturer A truck and from 0.20 to 0.24 g/bhp-h for the Manufacturer B truck, while failing MAW windows ranged from 0.54 to 0.70 g/bhp-h and 0.44 to 0.52 g/bhp-h, respectively, for the two trucks.

6.4 Conclusions and Recommendations

Although this study was limited to only two vehicles/engines, when combined information from the open literature, the results indicate that in-use NOx emissions are above the 0.2 g/bhp-hr level for a wide range of operation, and that there are higher emitting trucks that also can contribute disproportionately to the NOx inventory. Differences between different types of laboratory and on-road testing could be attributed to factors that impact engine out NOx and the SCR catalyst temperatures and performance, which in turn contribute to differences in tailpipe NOx emissions. The results suggest that further investigation is warranted to better understand differences between NOx emissions obtained during certification testing and real-world operation, and how gaps can be narrowed moving into the future.

It is likely that a combination of expanded certification criteria, tightened certification limits, and expanded in-use compliance procedures will be needed to provide greater control of in-use NOx emissions. In terms of certification procedures, a reduction of the certification standard to 0.02 g/bhp-hr is currently under consideration by CARB, and studies are on-going to evaluate techniques, such as improved thermal management, that could be used to achieve such levels. Additional provisions will also likely be needed to reduce emissions for vocations that operate under low load conditions, where the SCR efficiency can be much lower. This could include the development of additional certification cycles that would provide for better control of NOx emissions under low load conditions.

The current procedures for in-use compliance testing also have limitations, in that the exclusion criteria for NTE testing eliminates a large fraction of in-use operation. The MAW methodology, currently being used in Europe, provided improved coverage of in-use operation, and could provide a better methodology for capturing NOx emissions under a full range of operating conditions. It is also possible that greater control of in-use NOx emissions could be obtained by placing a greater emphasis on in-use compliance testing through the use of sensors that could be utilized to track emissions performance on a continuous basis.

References

Bartolome, C., Wang, L., Cheung, H., Lemieux, S., Heroy-Rogalski, K. and Robertson, W., 2018. Toward Full Duty Cycle Control: In-Use Emissions Tools For Going Beyond The NTE. Presentation at 28th CRC Real World Emissions Workshop, Garden Grove, CA, March.

Bishop, G.A., Schuchmann, B.G., Stedman, D.H., Lawson, D.R., 2012. Emission Changes Resulting from the San Pedro Bay, California Ports Truck Retirement Program. Environ. Sci. Technol. 46, 551–558.

Bishop, G.A., Schuchmann, B.G., Stedman, D.H., 2013. Heavy-Duty Truck Emissions in the South Coast Air Basin of California. Environ. Sci. Technol. 47, 9523−9529.

Boriboonsomsin, K., Johnson, K., Scora, G., Sandez, D., Vu, A., Durbin, T., Jiang, Y., and Burnette, A. (2017) Collection of Activity Data from On-Road Heavy-Duty Diesel Vehicles, Final Report for the California Air Resources Board under ARB Agreement No. 13-301, May.

Brown, J.E., Clayton, M.J., Harris, D.B., King, F.G., 2000, Comparison of the Particle Size Distribution of Heavy-Duty Diesel Exhaust Using a Dilution Tailpipe Sampler and an In-Plume Sampler during On-Road Operation; *J. Air & Waste Manage. Assoc. 50*, 1407-1416.

Brown, J.E., King Jr, F.G., Mitchell, W.A., Squier, W.C., Harris, D.B., and Kinsey, J.S., 2002, On-Road Facility to Measure and Characterize Emissions from Heavy-Duty Diesel Vehicles, Journal of the Air & Waste Management Association, 52:4, 388-395, DOI: 10.1080/10473289.2002.10470797.

Burgard, D.A., Bishop, G.A., Stedman, D.H., Gessner, V.H., Daeschlein, C., 2006, Remote sensing of in-use heavy-duty diesel trucks. Environ. Sci. Technol. 40, 6938−6942.

California Air Resources Board. 2013. Presentation entitled Mobile Source Emissions Inventory and Assessment Updates. October.

California Air Resources Board, 2017. EMFAC2017 An update to California On-road Mobile Source Emission Inventory. https://www.arb.ca.gov/msei/downloads/emfac2017_workshop_june_1_2017_final.pdf (access 7/5/2017).

California Air Resources Board, 2018. EMFAC2017 Volume III -Technical Documentation V1.0.2, March. https://www.arb.ca.gov/msei/downloads/emfac2017-volume-iii-technical-documentation.pdf (access 11/13/2018).

Carder, D., Gautam, M., Thiruvengadam, A., Besch, M., 2014. "In-Use Emissions Testing and Demonstration of Retrofit Technology for Control of On-Road Heavy-Duty Engines." Final Report by West Virginia University for the South Coast Air Quality Management District.

Cavataio, J.G., Girard, J.E., Patterson, Montreuil, C., Cheng, Y.S., Lambert, C.K., 2007. Laboratory Testing of Urea-SCR Formulations to Meet Tier 2 Bin 5 Emissions. SAE World Congress. Paper No. 2007-01-1575. http://papers.sae.org/2007-01-1575/

Clark, N. N., Gautam, M., Wayne, W. S., Lyons, D. W., Thompson, G. J., 2007. Heavy-duty vehicle chassis dynamometer testing for emissions inventory, air quality modeling, source apportionment, and air toxics emissions inventory. CRC Report No. E55/59.

Clark, N. N., Gautam, M., Wayne, W. S., Thompson, G. J., Lyons, D. W., 2004. California heavy heavy-duty diesel truck emissions characterization for project E-55/E-59 phase 1.5. CRC Report No. E55/59. Final Report for the Coordinating Research Council.

Clark, N. N., Gautam, M., Wayne, W. S., Thompson, G. J., Nine, R. D., Lyons, D. W., Buffamonte T., Xu S., Maldonado H., 2006. Regulated emissions from heavy heavy-duty diesel trucks operating in the south coast air basin. Soc. SAE Paper 2006-01-3395.

Clark, N.N., M. Gautam, M., W.S. Wayne, D. Lyons, W. F. Zhen, C. Bedick, R.J. Atkinson, and D.L. McKain. 2007a. Creation of the “Heavy Heavy-Duty Diesel Engine Test Schedule” for representative Measurement of Heavy-Duty Engine Emissions, CRC Report No. ACES-1, CRC Website at crcao.org, July.

Clark, N.N., F. Zhen, C. Bedick, M. Gautam, W. Wayne, G. Thompson, and D. Lyons, 2007b. Creation of the 16-Hour Engine Test Schedule from the Heavy Heavy-Duty Diesel Engine Test Schedule, CRC Report No. ACES-1-a, CRC Website at crcao.org, July.

Cocker III, D. R., Shah, S., Johnson, K., Miller, J. W., Norbeck, J., 2004a. Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. I Regulated Gaseous Emissions, Environ. Sci. & Technology. 38, 2182-2189.

Cocker, D.R.; Shah, S.D.; Johnson, K.J.; Zhu, X; Miller, J.W.; Norbeck, J.M., 2004b, Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 2. Sampling for Toxics and Particulate Matter, Environ. Sci. & Technology, 38, 6809-6816.

Code of Federal Regulations CFR, 2007. Supplemental emission test; test cycle and procedures. Office of the Federal Register National Archives and Records Administration. CFR Title 40 Part § 86.1360,2007.

Code of Federal Regulations CFR, 2007. Not-To-Exceed test procedures, Office of the Federal Register National Archives and Records Administration. CFR Title 40 Part § 86.1370, 2007.

Code of Federal Regulations CFR, 2011. Emission standards and supplemental requirements for 2007 and later model year diesel heavy-duty engines and vehicles, Office of the Federal Register National Archives and Records Administration. CFR Title 40 Part § 86.007, 2007.

Dallmann, T.R. and Harley, R.A., 2010, Evaluation of mobile source emission trends in the United States. J. Geophys. Res. 115, D14305.

Dallmann, T.R., Harley, R.A., and Kirchstetter, T.W., 2011, Effects of diesel particle filter retrofits and accelerated fleet turnover on drayage truck emissions at the Port of Oakland, Environ. Sci. Technol., 45, 10773–10779, doi:10.1021/es202609q,.

Dallmann, T.R., DeMartini, S.J., Kirchstetter, T.W., Herndon, S.C., Onasch, T.B., Wood, E.C., Harley, R.A., 2012, On-road measurement of gas and particle phase pollutant emission factors for individual heavy-duty diesel trucks. Environ. Sci. Technol. 46, 8511−8518.

Dallmann, T.R., Kirchstetter, T.W., DeMartini, S.J., and Harley, R.A., 2013, Quantifying On-Road Emissions from Gasoline-Powered Motor Vehicles: Accounting for the Presence of Medium- and Heavy-Duty Diesel Trucks, Environ. Sci. Technol., 47, 13873−13881

Dallmann, T.R., Onasch, T.B., Kirchstetter, T.W., Worton, D.R., Fortner, E.C., Herndon, S.C., Wood, E.C., Franklin, J., Worsnop, D.R., Goldstein, A.G., Harley, R.A., 2014, Characterization of particulate matter emissions from on-road gasoline and diesel vehicles using a soot particle aerosol mass spectrometer, Atmos. Chem. Phys. Discuss., 14, 4007–4049

Dallmann, T.R., Kirchstetter, T.W., DeMartini, S.J., and Harley, R.A., 2014, Quantifying on-road emissions from gasoline-powered motor vehicles: accounting for the presence of medium and heavy-duty diesel trucks, Environ. Sci. Technol., 47, 13873–13881, 25 doi:10.1021/es402875u, 2014.

Durbin, T.D., K. Johnson, D.R. Cocker, J.W. Miller, H. Maldonado, A. Shah, C. Ensfield, C. Weaver, M. Akkard, N. Harvey, J. Symon, T. Lanni, W.D. Bachalo, G. Payne, G. Smallwood, M. Linke, 2007. Evaluation and Comparison of Portable Emissions Measurement Systems and Federal Reference Methods for Emissions from a Back-up Generator and a Diesel Truck Operated on a Chassis Dynamometer. *Environ. Sci. & Technol.*, vol. 41, 6199-6204.

Durbin, T., Boriboonsomsin, K., Scora, G., Sandez, D., Vu, A., Johnson, K., Jiang, Y., Ventura, L.M.B, and Burnette, B., 2018, Collection of Tractor-Trailer Activity Data, Final report for the California Air Resources Board under contract No 14-302, March.

EPA, 2002. Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6: Analysis of BSFCs and Calculation of Heavy-Duty Engine Emission Conversion Factors. *EPA420-R-02-005*, January.

European Commission - DG ENTR (Enterprise), 2002, Study on Emission Control Technology For Heavy Duty Vehicles, "In-use Conformity Testing of Emissions Control Devices", May. http://ec.europa.eu/enterprise/automotive/pagesbackground/emission_control/vol_5-in-use_conformity_testing.pdf.

Gautam, M., Thompson, G.J., Carder, D.K., Clark, N.N., Shade, B.C., Riddle, W.C., and Lyons, D.W., 2001, Measurement of In-Use, On-Board Emissions from Heavy-Duty Diesel Vehicles: Mobile Emissions Measurement System, SAE Technical Paper No. 2001-01-3643.

Gautam, M., N. N. Clark, W. Riddle, R. Nine, W. S. Wayne, H. Maldonado, A. Agrawal, and M., Carlock. 2002. Development and initial use of a heavy-duty diesel truck test schedule for emissions characterization. In *Proceedings of Society of Automotive Engineeers (SAE) Fuels and Lubricants Meeting*; SAE Paper 2002-01-1753. SAE: Warrendale, PA.

Harris, D.B., King, F.G., and Brown, J.E., Development of On-Road Emission Factors for Heavy-Duty Diesel Vehicles Using a Continuous Sampling System; EPA-600/A-98-125 (NTIS PB99-106296). Presented at the A&WMA Emission Inventory: Programs and Progress Conference, Research Triangle Park, NC, October 10–13, 1995.

Herner, D. J.; Hu, S.; Robertson, H. W.; Huai, T.; Collins, F. J.; Dwyer, H.; Ayala, A., 2000. Effect of advanced after treatment for PM and NO_x control on heavy-duty diesel truck emissions. Environ. Sci. Technol. 43, 5928−5933.

Heywood, J.B., 1988. Internal combustion engine fundamentals.

Huai T.; Durbin T. D.; Miller J. W.; Pisano J.T.; Sauer C. G.; Rhee S. H.; et al. 2003, Investigation of the formation of NH_3 emissions as a function of vehicle load and operating condition. Environ. Sci. Technol. 37, 4841-4847.

Jiang, Y., Yang, J., Cocker, D., Karavalakis, G., Johnson, K.C. and Durbin, T.D., 2018. Characterizing emission rates of regulated pollutants from model year 2012+ heavy-duty diesel vehicles equipped with DPF and SCR systems. Science of the Total Environment, 619,765-771.

Johnson, D., 2002, ROVER – Real-time On-road Vehicle Emissions Reporter. Presentation for the Mobile Source Technical Review Committee, February.

Johnson, K.C., T.D. Durbin, D.R. Cocker III, J.W. Miller, R.J. Agama, N. Moynahan, G. Nayak, 2008. On-Road Evaluation of a PEMS for Measuring Gaseous In-Use Emissions from a Heavy-Duty Diesel Vehicle. SAE Int. J. Commer. Veh., 1, 200-209.

Johnson, K.C., Durbin, T.D., Cocker III, D.R., Miller, J.W., Bishnu D.K., Maldonado H., Moynahan N., Ensfield C., Laroo C.A.. 2009. On-Road Comparison of a Portable Emission Measurement System with a Mobile Reference Laboratory for a Heavy Duty Diesel Vehicle. Atmospheric Environment. Vol. 43, pp. 2877-2883.

Johnson, K.C., Durbin, T.D., Jung, H., Cocker III, D.R., Giannelli, R., Bishnu, D., 2010. Quantifying In-Use PM Measurements for Heavy Duty Diesel Vehicles. Environ. Sci. Technol., Vol. 45, pp. 6073-6079.

Khalek I., Bougher, T., Merritt P., and Zielinska B., 2011. Regulated and Unregulated Emissions from Highway Heavy-Duty Diesel Engines Complying with U.S. Environmental Protection Agency 2007 Emissions Standards Journal of Air and Waste Management Assoc. Vol 61, pp. 427-442.

Khalek, I. Blanks, M., Merritt, P., 2013, Phase 2 of The Advanced Collaborative Emissions Study, Final Report Project 03.17124, November. www.crcao.org/reports/recentstudies2013/.

Khan, M.Y., Johnson, K.C., Durbin, T.D., Jung, H., Cocker III, D., Bishnu, D., and Giannelli, R. 2012. Characterization of PM-PEMS for In-Use Measurements – Validation Testing for the PM-PEMS Measurement Allowance Program. Atmospheric Environment, 55, 311-318.

Lee. A., O'Cain, J., Avila. J., Lemieux, S., Karim, Sahay, K., Berdahi. S., Sahay, K., Na, K., Chang, O., and Macias, K., 2018. Findings fromcarb's heavy-duty in-use compliance testing program. Presentation at 28th CRC Real World Emissions Workshop, Garden Grove, CA, March.

Miller, J. W., Johnson, C. K., Durbin, T., Dixit, P., 2013. In-Use Emissions Testing and Demonstration of Retrofit Technology for Control of On-Road Heavy-Duty Engines. Final Report by the University of California at Riverside to the South Coast Air Quality Management District under Contract No. 11612.

Misra, C., Collins, J.F., Herner, J.D., Sax, T., Krishnamurthy, M., Sobieralski, W., Burntizki, M., and Charnich, D. 2013. In-Use NOx Emissions from Model Year 2010 and Heavy-Duty Diesel Engines Equipped with Aftertreatment Devices, Environ. Sci. Technol. 47, 7892−7898.

Misra, C., Yoon, S., Collins, J., Chernich, D., Herner, J., 2016. Evaluating In-Use SCR Performance: Older vs. Late MY Engines. Presentation at 26th CRC Real World Emissions Workshop, Newport Beach, CA, March.

O'Cain, J., Lemieux, S., Karim, J., Sahay, K., Chang, O., Lee., D. and Sardar, S., 2016. Heavy-duty in-use compliance pilot program. Presentation at 26th CRC Real World Emissions Workshop, Newport Beach, CA, March.

Quiros, D.C., Ham, W.A., Ianni, R., Smith, J.D., Sobieralski, W., Chernich, D.J., Hu, S., Huai, T., 2017. Assessing Emission Control System Durability using ARB's Pilot Heavy-Duty Truck and Bus Surveillance Program. Presentation at the 27th CRC Real World Emissions Workshop, Long Beach, CA, March.

San Pedro Bay Ports Clean Air Action Plan Technical Report (CAAP), The Port Of Long Beach and Los Angeles, 2006.

Sandhu, G.S., Sonntag, D., Sanchez, J., 2018, Identifying Areas of High NOx Operation in Heavy-Duty Vehicles, presentation at the 28th CRC Real-World Emissions Workshop, March, Garden Grove, CA.

Sawyer, R. F.; Harley, R. A.; Cadle, S. H.; Norbeck, J. M.; Slott, R.; Bravo, H. A., 2000, Mobile Sources Critical Review. Atmos. Environ. 34, 2161−2181.

Shah, S., Johnson, C. K., Miller, J. W., Cocker, R. D., 2006. Emission rates of regulated pollutants from on-road heavy-duty diesel vehicles. Atmos. Environ. 40, 147−153.

Sharp, C. A., Webb, C. C., Neely, G. D., Smith, I., 2017. Evaluating technologies and methods to lower nitrogen oxide emissions from heavy-duty vehicles by Southwest Research Institute to the California Air Resources Board under Contract No. 13-312.

Spears, M., 2018. Needs and Opportunities for Reducing Real World NOx Emissions from Heavy-Duty On-Highway Engines. Presentation at 28th CRC Real World Emissions Workshop, Garden Grove, CA, March.

Strots, O. V.; Santhanam, S.; Adelman, J. B.; Griffin, A. G.; Derybowski, M. E., 2009. Deposit formation in urea-SCR systems. SAE Technical Paper 2009-01−2780, 2009.

Texas A&M Transportation Institute, 2013, Heavy-Duty Diesel Inspection and Maintenance Pilot Program.

Tan, Y., Collins, J., Yoon, S., Herner, J., Henderick, P., Montes, T., Ham, W., Howard, C., Hu, S., Johnson, K., Scora, G., Sandez, D., Durin, T., 2018. NOx Emission Estimates from the

Activity Data of On-Road Heavy-Duty Diesel Vehicles. Presentation at 28th CRC Real World Emissions Workshop, Garden Grove, CA, March.

Thiruvengadam, A, Besch, M. C., Thiruvengadam, P., Pradhan S., Carder, D.,Kappanna, H., Gautam, M., 2015. Emission Rates of Regulated Pollutants from Current Technology Heavy-Duty Diesel and Natural gas goods, movement Vehicles. Environ. Sci. Technol 49 (8), 5236-5244.

Thiruvengadam, A, Besch, M. C., Thiruvengadam, P., Pradhan S., Carder, D.,Kappanna, H., Gautam, M., 2015. Emission Rates of Regulated Pollutants from Current Technology Heavy-Duty Diesel and Natural gas goods, movement Vehicles. Environ. Sci. Technol 49 (8), 5236-5244.

Thiruvengadam, A., Saroj, Pradhan, S., Demirgok, B., Besch, M., Carder, D., Quiros, D., Hu, S., Tao, Huai, Oshinuga, A., Chernich, D., Gautam, M., 2016, In-use Emissions from Current Model Year Heavy-duty Diesel and Natural Gas Trucks – Evaluation of NTE vs. Alternative Metrics. Presentation at 26th CRC Real World Emissions Workshop, Newport Beach, CA, March

TIAX, 2011. Development of a Drayage Truck Chassis Dynamometer Test Cycle, Report for the Port of Long Beach/Contract HD-7188 Port of Los Angeles/Tetra Tech, September.

Tu, J., Berdahl, S., Tran, T., O'Cain, J., Karim, J., Sardar, S., Lemieux, S., Huai, T., 2016. Study of heavy-duty vehicle emissions during in-use compliance testing. Presentation at 26th CRC Real World Emissions Workshop, Newport Beach, CA, March.

U.S. Environmental Protection Agency; Heavy Trucks, Buses, and Engines; Regulations and Related Documents; see http://www.epa.gov/otaq/hd-hwy.htm#regs.

U.S. Environmental Protection Agency, 2004. Working Group On Off- Cycle Emissions, "EPA Answers to Questions from March 22nd 2004 NTE Presentation". http://www.oica.net/htdocs/WWH/Off%20cycle/7th%20meeting/Informal%20Doc%20No%2014%20-%20EPA%20answers%20to%20NTE%20Questions%20from%206th%E2%80%A6.pdf.

Zhao., Y., Hu, J., Hua, L., Shuai, S., Wang, J. 2011. Ammonia Storage and Slip in a Urea Selective Catalytic Reduction Catalyst under Steady and Transient Conditions. IE&C, 50, 11863–11871.

Yoon, S., Berdahl, S., O'Cain, J., Bishnu, D., Misra, C., Collins, J., Chernich, D., Karim, J., Herner, J., 2016. Comparison of Heavy-Duty In-Use Engine Compliance Methods for Controlling NOx Emissions. Presentation at 26th CRC Real World Emissions Workshop, Newport Beach, CA, March.

Appendix A. Vehicle Inspection Report

Veh. No.:____________________ VIN:____

ARRIVAL DATE:	ARRIVAL TIME:
AGENCY RELEASE SIGNATURE:	
DELIVERED BY:	

DEPARTURE DATE:	DEPARTURE TIME:
UCR ENGINEER RELEASE SIGNATURE:	
RETURNED TO:	

Retest? ☐Yes ☐No. If Yes, reason for retest:____

Engine Compartment

			REMARKS
OIL LEVEL:	☐ FULL	☐ LOW	
COOLANT LEVEL:	☐ FULL	☐ LOW	
POWER STEERING FLUID:	☐ FULL	☐ LOW	
CONDITION OF BELTS:	☐ GOOD	☐ WORN	
CONDITION OF AIR FILTER:	☐ CLEAN	☐ DIRTY	
VISIBLE EXHAUST LEAKS:	☐ YES	☐ NO	
VISIBLE FLUID LEAKS:	☐ YES	☐ NO	
ENGINE APPEARANCE:	☐ CLEAN	☐ GREASY	

Equipment

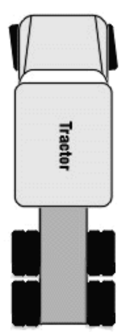
SERVICE BRAKES:	☐ GOOD	☐ POOR	☐ TOUCHY	
PARKING BRAKES:	☐ GOOD	☐ POOR		
POWER DIVIDER:	☐ GOOD	☐ DEFECTIVE	☐ NOT EQUIPPED	
TRANSMISSION:	☐ NORMAL	☐ SHIFTS HARD	☐ NOISY	
LUG NUT COVERS:	☐ YES	☐ NO	NUMBER MISSING:	
TIRE CONDITION:	FRONT		REAR	
	☐ GOOD	☐ WORN	☐ GOOD	☐ WORN
REMARKS:				

Vehicle Interior

UPHOLSTERY:	☐ CLEAN	☐ DIRTY	☐ STAINED	☐ DAMAGED	REMARKS:
CARPET:	☐ CLEAN	☐ DIRTY	☐ STAINED	☐ DAMAGED	REMARKS:
GENERAL APPEARANCE:	☐ CLEAN	☐ DIRTY		REMARKS:	
GAUGES AND CONTROLS:	☐ OPERATE PROPERLY		☐ DEFECTIVE	REMARKS:	

Vehicle Exterior (mark the location and describe any dents, scratches, damaged lights, mirrors etc. when the vehicle was received by UCR):

1. ____________________
2. ____________________
3. ____________________
4. ____________________
5. ____________________
6. ____________________
7. ____________________
8. ____________________
9. ____________________



10. ____________________
11. ____________________
12. ____________________
13. ____________________
14. ____________________
15. ____________________
16. ____________________
17. ____________________
18. ____________________

Was this vehicle damaged while in UCR custody? ☐Yes ☐No. If Yes, explain:____________________

General Remarks

Vehicle Information Form

☐ Agency:______________________________

☐ Address:______________________________

☐ Contact Person: ______________________________

☐ Phone Number/Email: ______________________________

☐ Vehicle Manufacturer/ChassisType:______________________________

☐ Vehicle Occupancy Capacity: Seated _______________ Standing_______________

☐ Agency Vehicle #:_______________Licence Plate # :_______________

☐ Vehicle Model Year: ________VIN #:(17 DIGIT)______________________________

☐ GVWR Front: Middle: Rear:

☐ Curb Weight: Front: Middle: Rear:

☐ Vehicle Dimensions: Length: Width: Height:

☐ Mileage Odometer: Hub Meter:

☐ Engine Manufacturer: _______________ Model: _______________Year:_______________

☐ Engine Serial#: _______________EPA Family Cert. #:_______________

☐ Engine Displacement:________ # of Cylinders: Configuration:

☐ Max. Engine Power (hp) _______________ hp @ _______________ RPM

☐ Max. Engine Torque:(ft-lb.) _______________ ft-lbs @ _______________ RPM

☐ Idle Speed:_______________ Governed Speed: High Idle:

☐ Electronic Engine Control (☐Y/☐N) If Yes, Rebuild:______________________________

☐ Engine Rebuilt (☐Y/☐N) If Yes, Year of Rebuild:______________________________

☐ Primary Fuel Type: ☐D1 ☐D2 ☐CNG ☐LNG ☐ BD (%): Other (Specify):

☐ Number of Fuel Tanks: __________Capacity: ______________________________

☐ Oil Type: Weight ____________________Brand ____________________

Aftertreatment Configuration:

- ☐ Oxidation Catalyst (☐Y/☐N) Manufacturer______________________________
- ☐ PM Trap (☐Y/☐N) Manufacturer______________________________
- ☐ SCR (☐Y/☐N) Manufacturer______________________________
- ☐ NOx Absorber (☐Y/☐N) Manufacturer______________________________
- ☐ NH3 Catalyst (☐Y/☐N) Manufacturer______________________________
- ☐ Other (☐Y/☐N) Manufacturer______________________________

☐ Total Number of Axles:_______________ Number of Drive Axles:

☐ Transmission Type: Auto/Manual ____________________Speeds:_______________

☐ Transmission Manufacturer ______________________________

☐ Hybrid Technology (☐Y/☐N) Comment: ______________________________

☐ Tire Size:_______________Tire Manufacturer:_______________Type(☐Bias ☐Radial ☐Other)

☐ Tailpipe Size:________Location/Configuration: ______________________________

Appendix B. Chassis Dynamometer And Engine Dynamometer Test Cycles

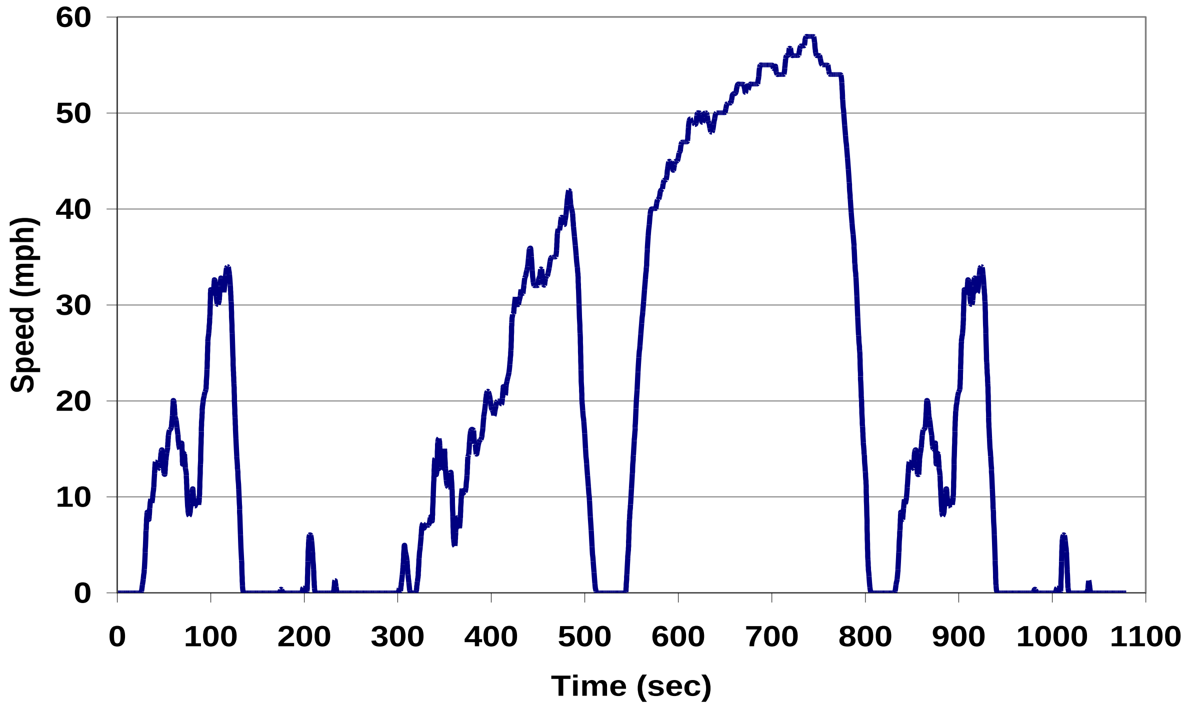


Figure B-1. Speed/Time Trace for a UDDS cycle for the chassis dynamometer.

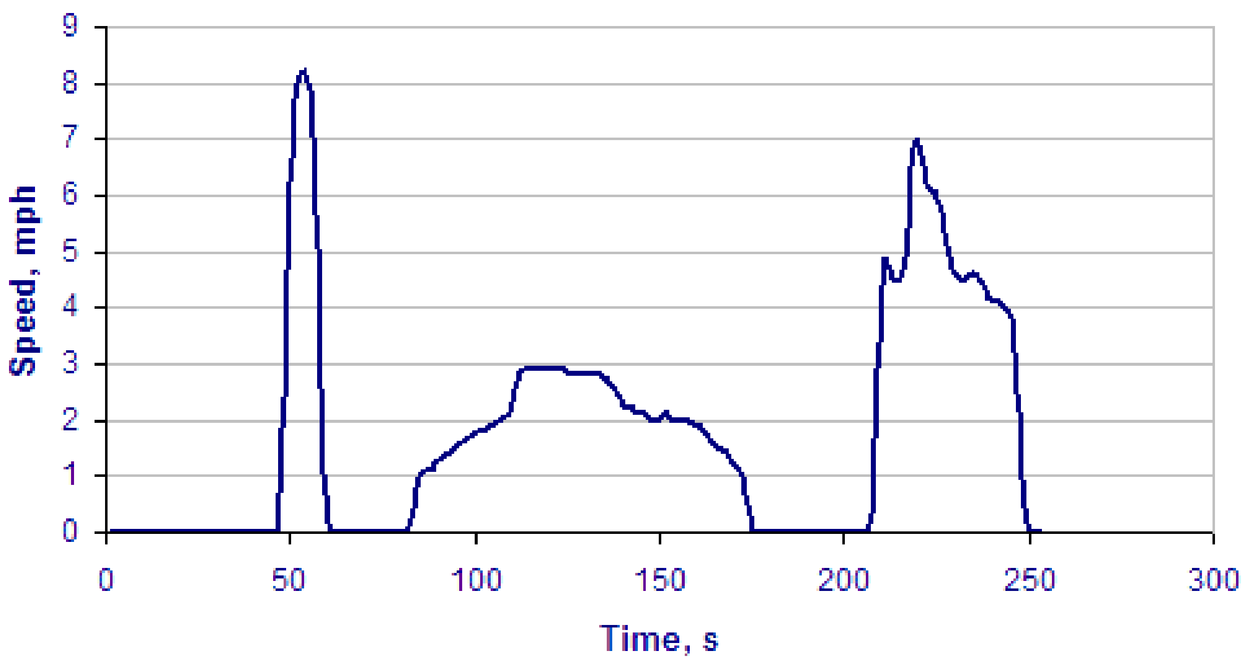


Figure B-2. Speed/Time Trace for a HHDDT-Creep cycle for the chassis dynamometer.

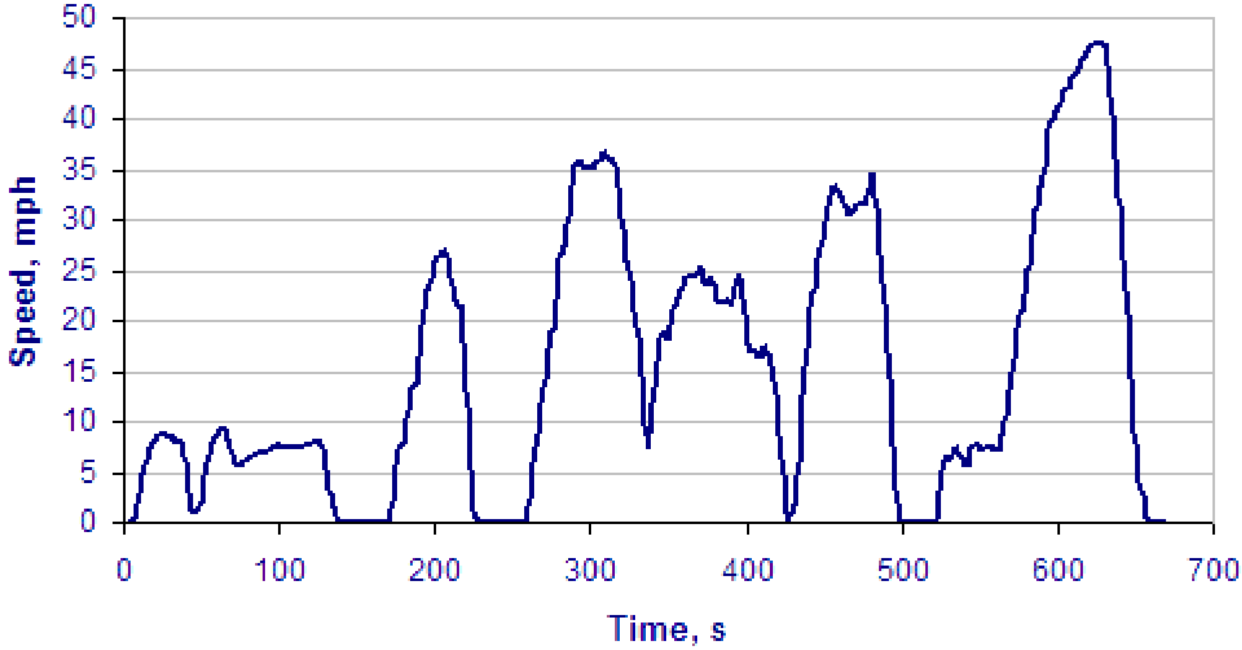


Figure B-3. Speed/Time Trace for a HHDDT-Transit cycle for the chassis dynamometer.

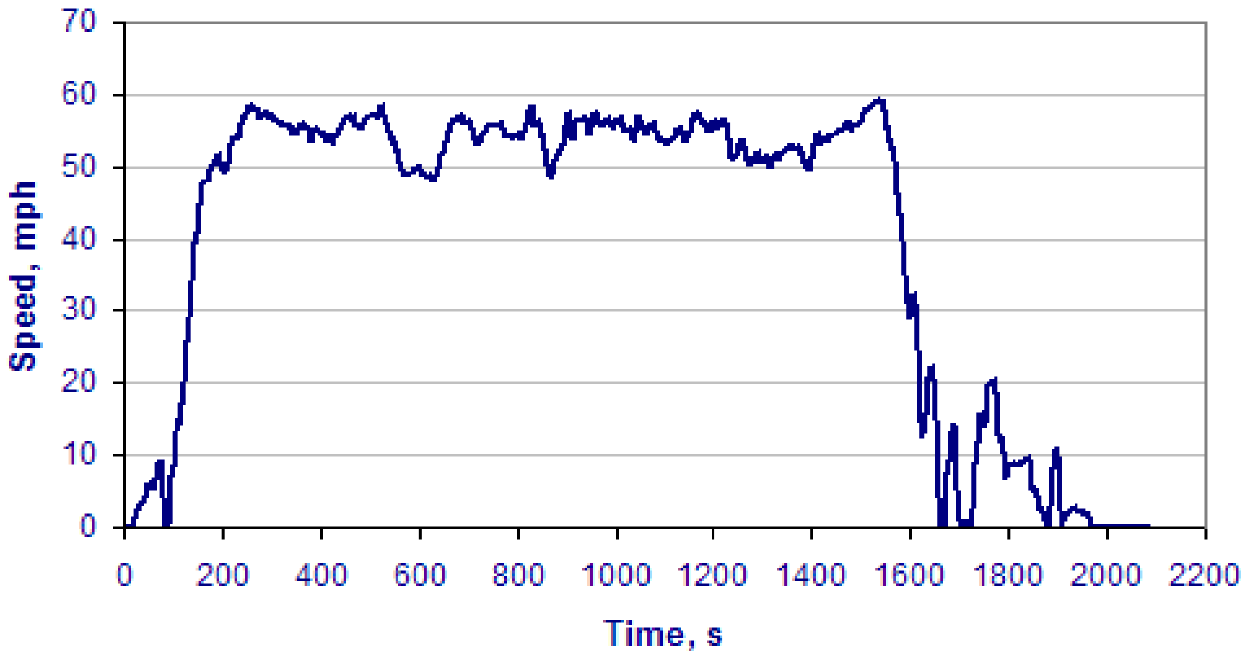


Figure B-4. Speed/Time Trace for a HHDDT-Cruise cycle for the chassis dynamometer.

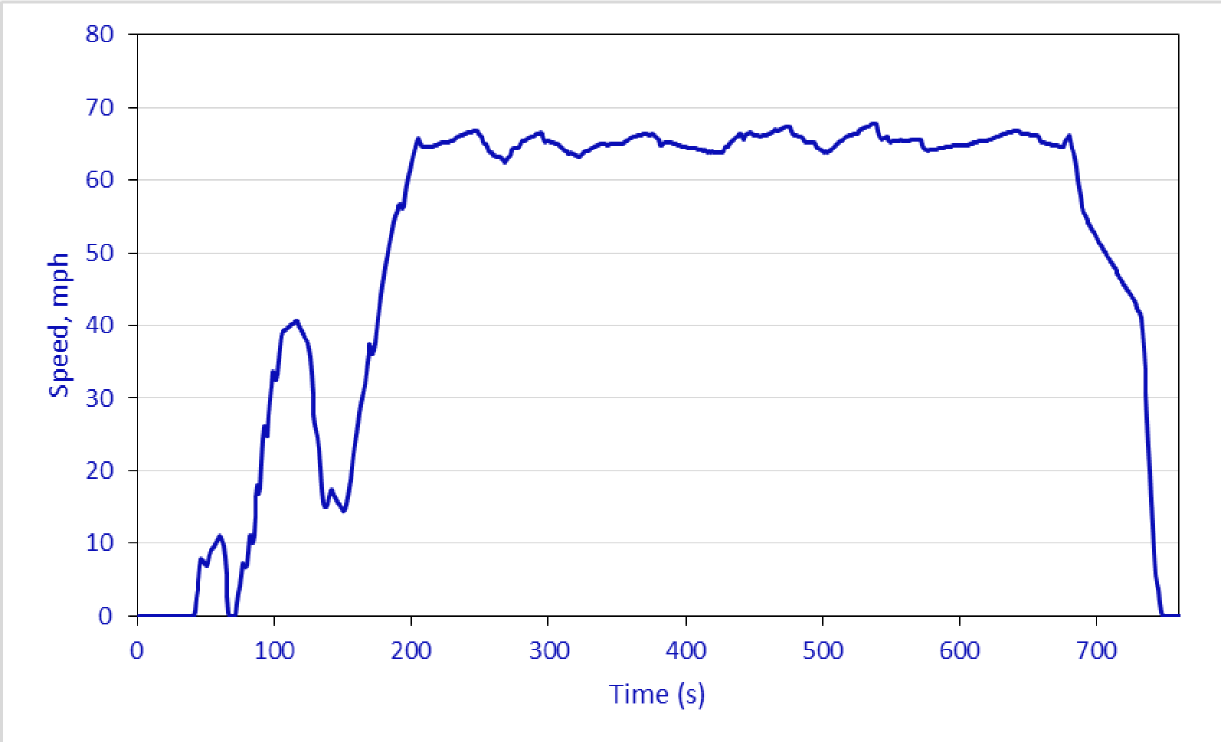


Figure B-5. Speed/Time Trace for a HHDDT-Short cycle for the chassis dynamometer.

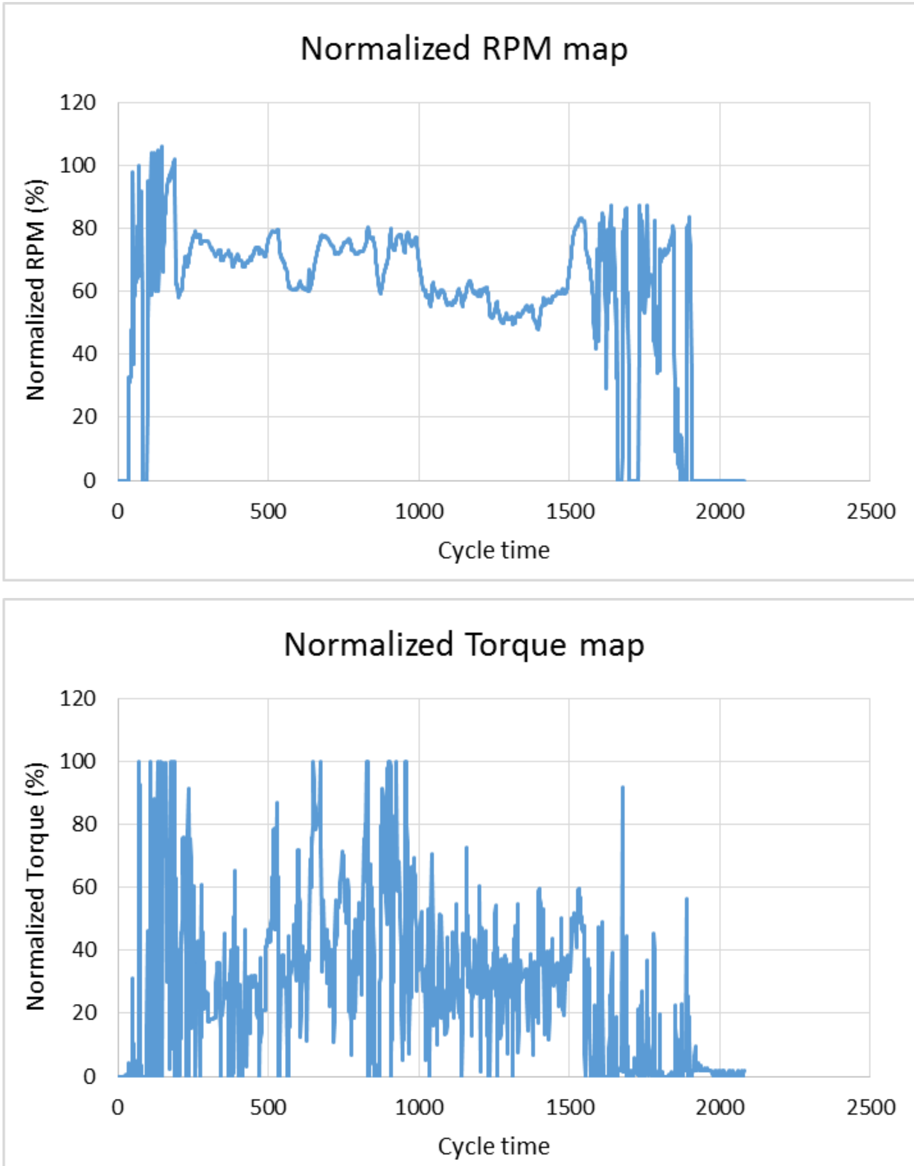


Figure B-6. Normalized RPM and Torque Map Trace for a HHDDT-Cruise cycle for the engine dynamometer.

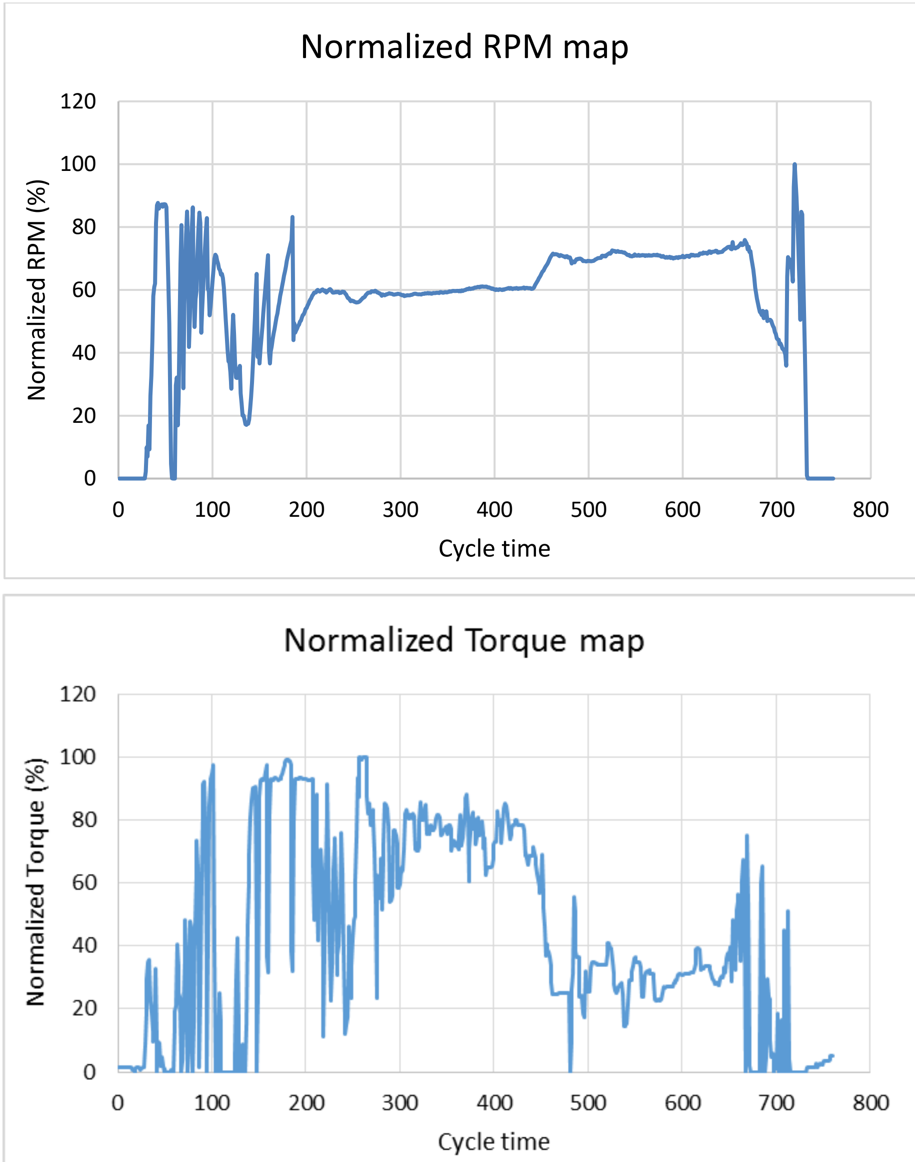


Figure B-7. Normalized RPM and Torque Map Trace for a HHDDT-Hi-speed Cruise cycle for the engine dynamometer.

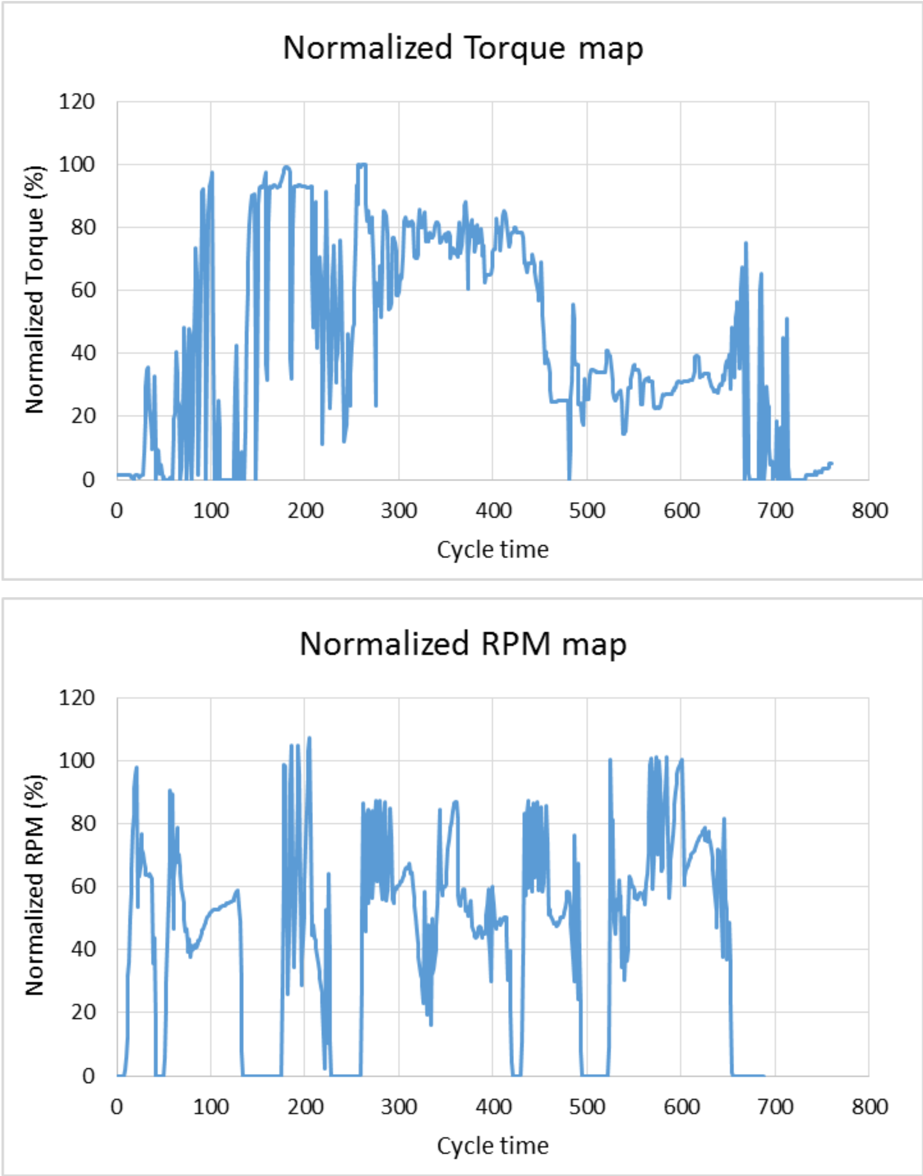
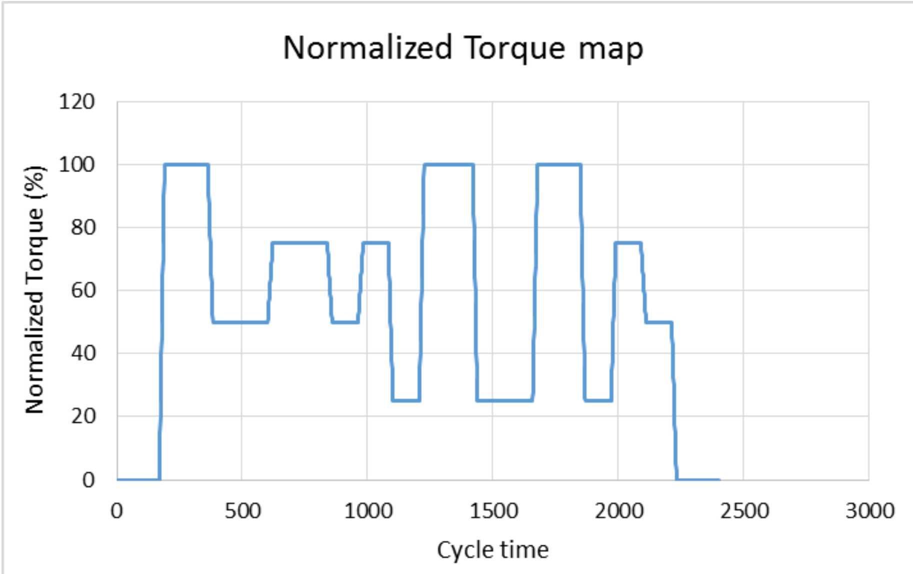


Figure B-8. Normalized RPM and Torque Map Trace for a HHDDT-Transient cycle for the engine dynamometer.



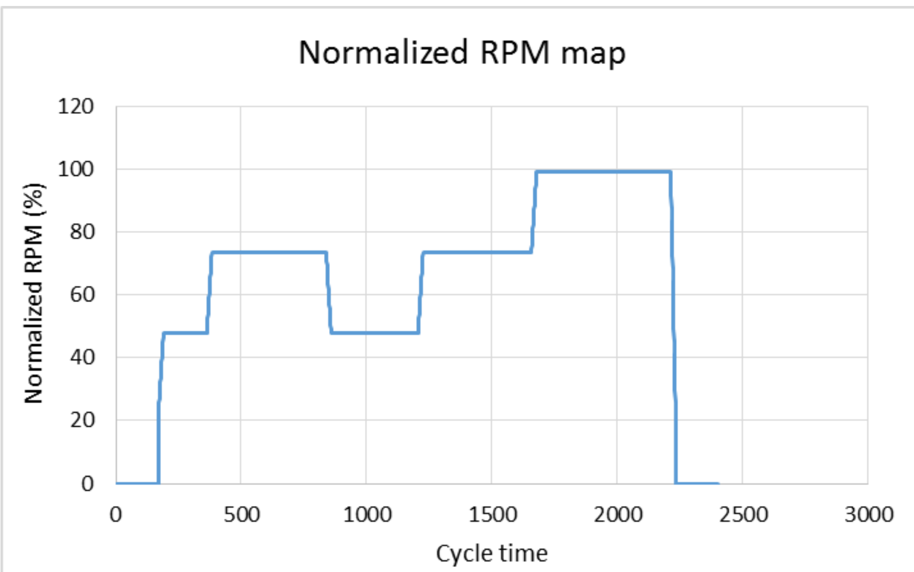


Figure B-9. Normalized RPM and Torque Map Trace for a RMC cycle for the engine dynamometer.

Appendix C. Description of Facilities

CE-CERT Heavy-Duty Chassis Dynamometer Laboratory

UCR has installed a heavy-duty tandem axle truck chassis dynamometer in the facility's research area, in conjunction with Mustang Dynamometer. The development of the chassis dynamometer design was based on target vehicles in the medium to heavy-duty diesel vehicle range. This high performance 48" Electric Chassis Dynamometer has Dual Direct Connected, 300 Hp AC Motors individually attached to each roll set (model MD-AC/AC-300.48/300.48-45,000lb-HD-TANDEM). The dynamometer is capable of simulating exacting road load & inertia forces to a vehicle operating over a range of different driving conditions including highway cruise, urban driving, and other typical on road driving conditions, with the designed based on 17 different drive cycles. The robust dynamometer can continuously absorb/motor loads in excess of 600 HP from 45 to 80 mph and intermittently absorb/motor loads in the range of 1,200 Hp. The dynamometer is able perform vehicle inertia simulation across a vehicle weight range of 10,000 to 80,000 lb. CE-CERT's Mobile Emissions Laboratory (MEL) is used directly in conjunction with this facility for certification type emissions measurements.

CE-CERT Engine Dynamometer Test Cell

CE-CERT's Heavy-Duty Engine Dynamometer Test Facility is designed for a variety of applications including verification of diesel aftertreatment devices, certification of alternative diesel fuels, and fundamental research in diesel emissions and advanced diesel technologies. The engine dynamometer facility components were provided as a turnkey system by Dyne Systems of Wisconsin. CE-CERT's Mobile Emissions Laboratory (MEL) is used directly in conjunction with this facility for certification type emissions measurements.

The test cell is equipped with a 600 horsepower (hp) GE DC electric engine dynamometer that was obtained from the EPA's National Vehicle and Fuels Emission Laboratory in Ann Arbor, MI. The dynamometer is capable of testing approximately 85% of the engines used in on-road applications, and will primarily be used for engines in the 300 to 600 hp range. A charge air conditioning system was obtained from Dynamometer Air of North Carolina to provide temperature/ humidity control for the engine intake air, with an accuracy of ±2°C from the setpoint.

Mobile Emissions Laboratory

CE-CERT's Mobile Emissions Laboratory (MEL) is a complete emissions laboratory housed within a 53-foot truck trailer. The MEL is designed to make laboratory-quality emissions measurements of heavy-duty trucks under actual operating conditions, or to be used in conjunction with stationary laboratories for heavy-duty engine dynamometer testing, heavy-duty chassis dynamometer testing, or generators. The laboratory contains a dilution tunnel, analyzers for gaseous emissions, and ports for particulate measurements. The MEL is designed and operated to meet the specifications of Title 40 of the CFR, Part 1065. The mobile laboratory contains a suite of gas-phase analyzers on shock-mounted benches. The gas-phase analytical instruments measure NO_x, methane (CH_4), THC, CO, and CO_2 at a frequency of 1 hertz (Hz) and were selected based on optimum response time and on road stability. The capabilities and details of the MEL design and specifications are described in Cocker[15,16] The MEL has been verified against CARB's heavy-duty diesel lab, the Department of Energy (DOE) lab in Denver, and a laboratory at Southwest Research (SwRI) in San Antonio. Recently, the MEL was used for the on-road verification of the Measurement Allowance program to verify portable emissions measurement system for in-use compliance testing.

[15] Cocker, D.R. III, Shah, S.D., Johnson, K., Miller, J.W., and Norbeck, J.M., 2004. "Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 1. Regulated Gaseous Emissions" Environ. Sci. Technol., Vol. 38, p. 2182-2189.

[16] Cocker, D.R. III, Shah, S.D., Johnson, K., Zhu, X., Miller, J.W., and Norbeck, J.M., 2004. "Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 2. Sampling for Toxics and Particulate Matter. Emissions" Environ. Sci. Technol., Vol. 38, p. 6809-6816.

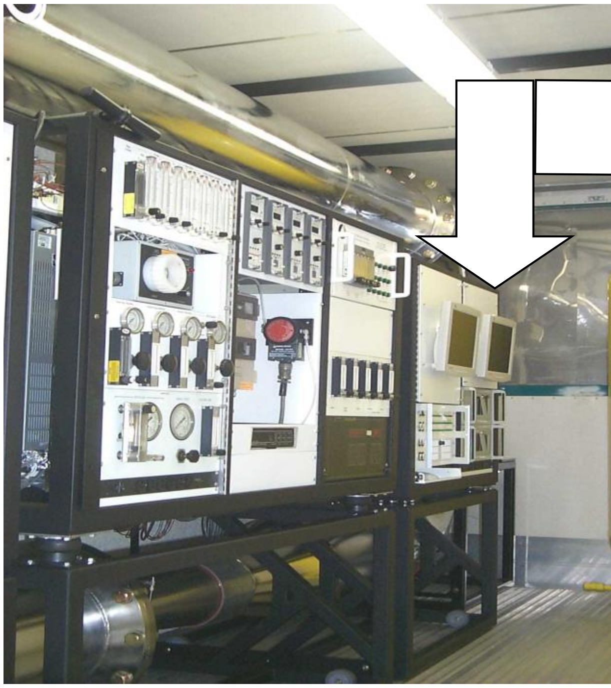


Figure 1. Left: Trailer laboratory interior, looking forward. Dilution tunnel travels beneath, forward of, and above analytical instruments. Connector at the front captures emissions as the truck pulls the trailer. Above: Trailer laboratory in operation at the California Speedway.

Portable Emissions Measurement System

CE-CERT is equipped with a fully 1065 approved gaseous and PM PEMS system for on-road and off-road applications. The system utilizes the AVL M.O.V.E. system for gaseous emission measurements and the AVL 494 system for PM measurements. The AVL M.O.V.E. is equipped with a non-dispersive ultraviolet (NDUV) analyzer for measuring oxides of nitrogen (NO and NO_2), a non-dispersive infrared (NDIR) analyzer for measuring CO and CO_2, and a flame ionization detector (FID) for measuring total hydrocarbons (THC). The gaseous data is measured as a concentration and is time aligned and flow weighted to the exhaust flow for total mass reporting. All time alignment and flow weighting is performed as part of the post processor systems for both PEMS. The exhaust flow meter is integrated with the gaseous PEMS and is designed to work with a wide range of exhaust flows and dynamics of transient vehicle testing. The exhaust flow meter uses differential pressure as its measurement principle.

The PM PEMS measurement system is the AVL 494 PM system, which was released in mid-2010, combines AVL's 483 micro soot sensor (MSS) with their gravimetric filter module (GFM) option. The AVL 483 MSS measures the modulated laser light absorbed by particles from an acoustical microphone. The measurement principle is directly related to elemental carbon (EC) mass (also called soot), and is robust and found to have good agreement with the reference gravimetric method for EC dominated PM. The GFM is then utilized in conjunction with a post processor that utilizes the filter and a soluble organic fraction (SOF) and Sulfate model to estimate total PM from the soot and gravimetric filter measurements. One gravimetric filter can be sampled per day and continuous PM concentration is recorded at 1 Hz with an option of 10Hz data. The combined MSS+GFM system recently received type approval by EPA as a total PM measurement solution for in-use testing, thus making it one of the few 1065 compliant PM PEMS systems.

CE-CERT has developed a platform to allow the gaseous and PM PEMS to be installed in a variety of different applications. A picture of the installation of the system on a piece of off-road construction equipment is provided below. Note that the picture is based on the first version of the system that utilized a Semtech DS gaseous emissions analyzer. The adaption of the system of the AVL M.O.V.E. system was completed in 2011.

Real-time ECM, gaseous, and PM PEMS emissions systems on in-service construction equipment.

Appendix D. Coast Down Calculations

The method for determining coast down coefficients at UCR was published and evaluated as part of a previous report to the South Coast Air Quality Management District[17]. Typical coastdown procedures assume that vehicle loading force is a function of vehicle speed, drag coefficient, frontal area and tire rolling resistance coefficient and takes the form of equation 1:

$$M\frac{dV}{dt} = \frac{1}{2}\rho A C_D V^2 + \mu Mg\cos(\theta) + Mg\sin(\theta) \qquad \text{(Equation 1)}$$

Where:

M = mass of vehicle in lbs

ρ = density of air in kg/m^3.

A = frontal area of vehicle in square feet, see Figure 1

C_D = aerodynamic drag coefficient (unitless).

V = speed vehicle is traveling in mph.

μ = tire rolling resistance coefficient (unitless).

g = acceleration due to gravity = 32.1740 ft/sec^2.

θ = angle of inclination of the road grade in degrees.

Constant parameters for equation 1	
μ	0.007
C_D	0.75 for Truck 0.79 for Bus 0.80 for Refuse Truck
g	32.1740 ft/sec^2

Assuming that the vehicle loading is characteristic of this equation, speed-time data collected during the coast down test can be used with static measurements (Mass, air density, frontal area, and grade) to solve for drag coefficient (CD) and tire rolling resistance coefficient (μ). The frontal area is measured based on the method described in Figure C-1 below.

However, experience performing in-use coast downs is complex and requires grades of less than 0.5% over miles of distance, average wind speeds < 10 mph ± 2.3 mph gusts and < 5 mph cross wind[18]. As such, performing in-use coast downs in CA where grade and wind are unpredictable are unreliable where a calculated approach is more consistent and appropriate. Additionally vehicles equipped with

[17] Draft Test Plan Re: SCAQMD RFP#P2011-6, "In-Use Emissions Testing and Demonstration of Retrofit Technology for Control of On-Road Heavy-Duty Engines", October 2011

[18] EPA Final rulemaking to establish greenhouse gas emissions standards and fuel efficiency standards for medium and heavy duty engines and vehicles, Office of Transportation and Air Quality, August 2011 (Page 3-7) and J1263 coast down procedure for fuel economy measurements

automatic transmissions have shown that on-road loading is also affected by the characteristics of the vehicle transmission, especially when reverse pumping losses at low speed begin to dominate.

UCR's and others recommend a coast down method that uses a characteristic coast down equation, with a measured vehicle frontal area (per SAE J1263 measurement recommendations), a tire rolling resistance of 0.007, and a Cd 0.75 (Truck) 0.79 (Bus) and 0.80 (Refuse Truck) in the above equation to calculate coast down times to be used for calculating the A, B, C coefficients in equation 2 for the dynamometer operation parameters. This approach is consistent and has proven very reliable for chassis testing heavy duty vehicle and has been used for years. For evaluation of aerodynamic modifications and body styles, UCR recommends investing the time perform in-use coast downs.

$Y = C(x^2) + B(x) + A$

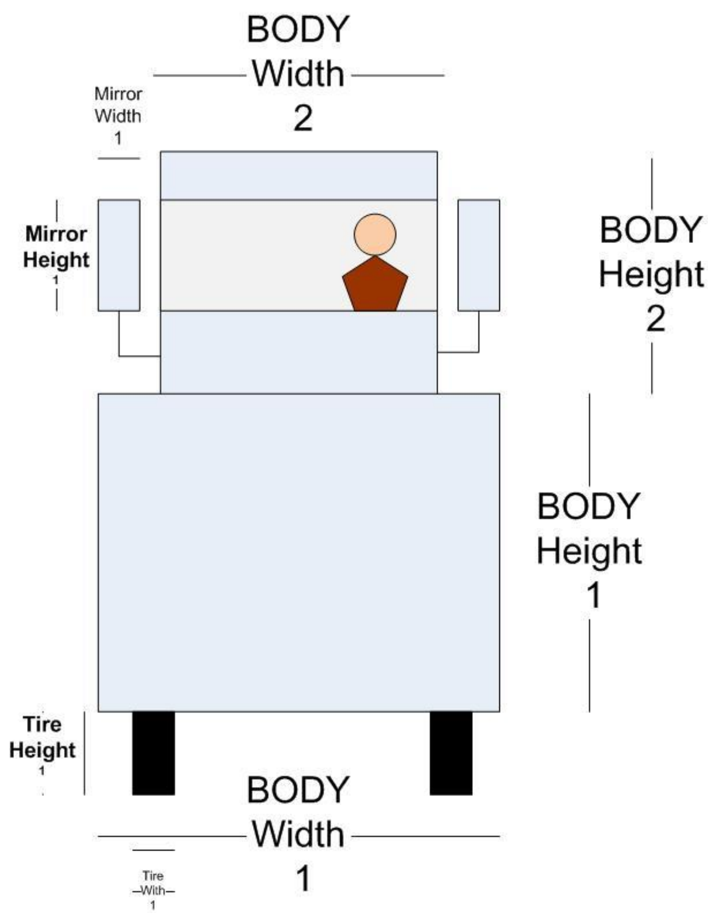


Figure D-1 Vehicle frontal area dimensions method

Appendix E. Engine Dynamometer Test Cycles

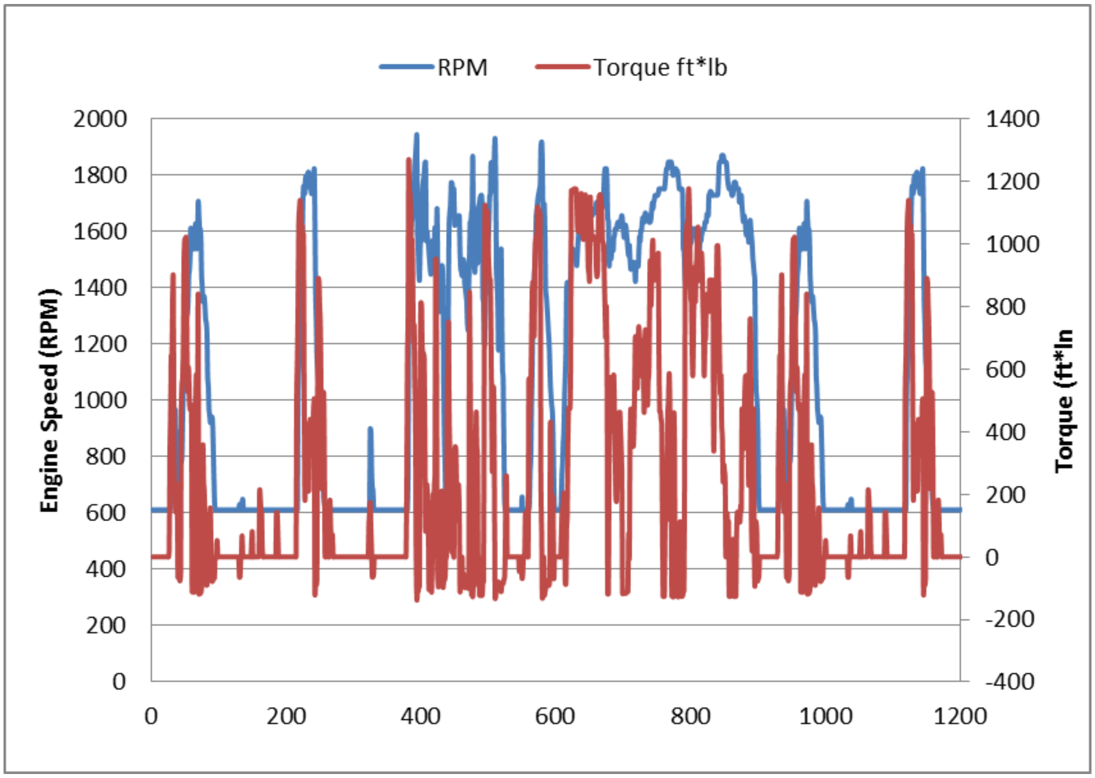


Figure E-1 Federal Test Procedure (FTP) certification cycle for the engine dynamometer.

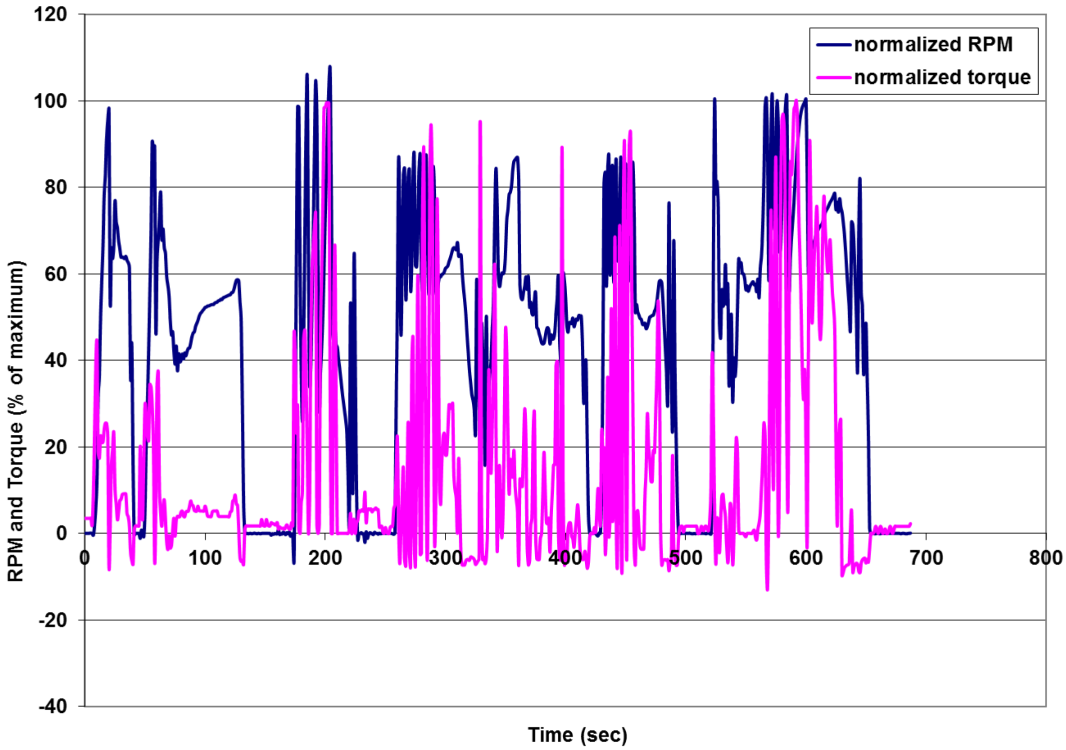


Figure E-2. Normalized RPM/torque Trace for a HHDDT-Transit cycle for the engine dynamometer

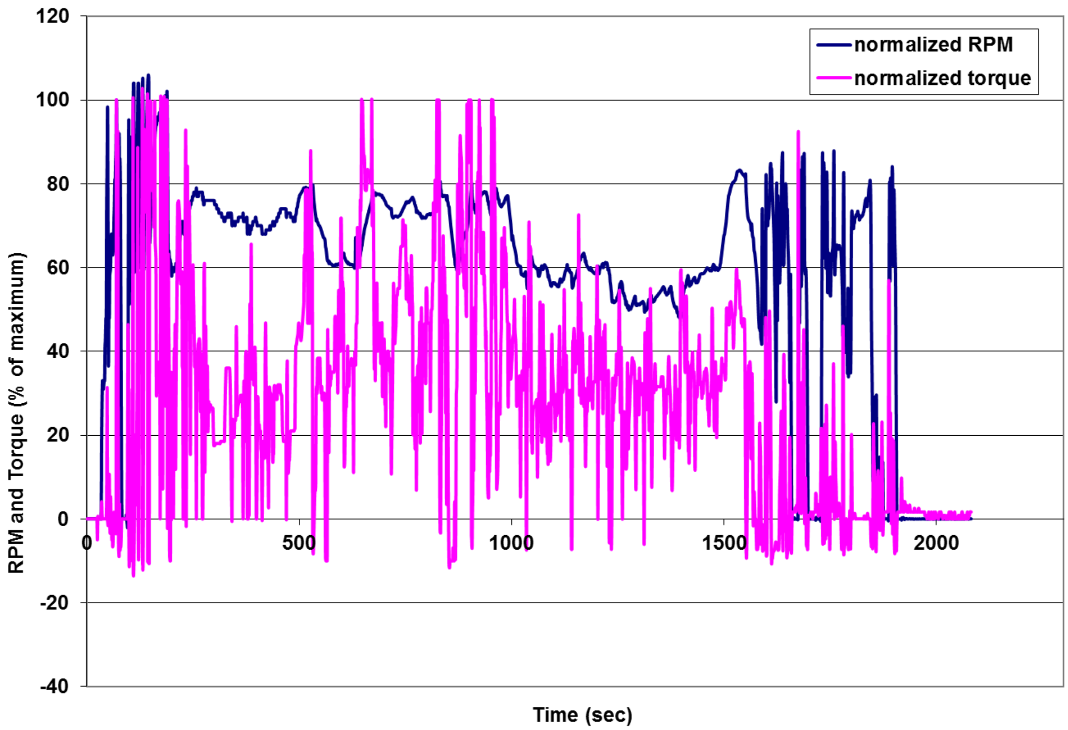


Figure E-3. Normalized RPM/torque Trace for a HHDDT-Cruise cycle for the engine dynamometer

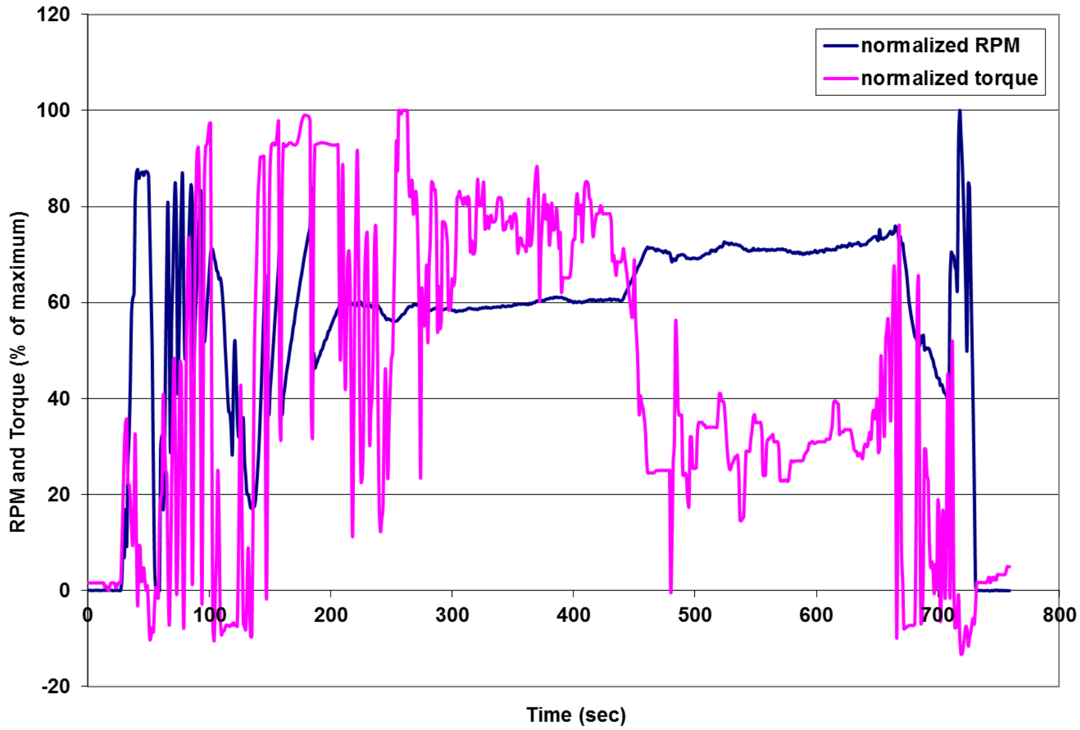


Figure E-4. Normalized RPM/torque Trace for a HHDDT-S cycle for the engine dynamometer

RMC mode	Time in mode (seconds)	Engine speed [1,2]	Torque (percent) [2,3]
1a Steady-state	170	Warm Idle	0
1b Transition	20	Linear Transition	Linear Transition.
2a Steady-state	173	A	100
2b Transition	20	Linear Transition	Linear Transition.
3a Steady-state	219	B	50
3b Transition	20	B	Linear Transition.
4a Steady-state	217	B	75
4b Transition	20	Linear Transition	Linear Transition.
5a Steady-state	103	A	50
5b Transition	20	A	Linear Transition.
6a Steady-state	100	A	75
6b Transition	20	A	Linear Transition.
7a Steady-state	103	A	25
7b Transition	20	Linear Transition	Linear Transition.
8a Steady-state	194	B	100
8b Transition	20	B	Linear Transition.
9a Steady-state	218	B	25
9b Transition	20	Linear Transition	Linear Transition.
10a Steady-state	171	C	100
10b Transition	20	C	Linear Transition.
11a Steady-state	102	C	25
11b Transition	20	C	Linear Transition.
12a Steady-state	100	C	75
12b Transition	20	C	Linear Transition.
13a Steady-state	102	C	50
13b Transition	20	Linear Transition	Linear Transition.
14 Steady-state	168	Warm Idle	0

[1] Speed terms are defined in 40 CFR part 1065.
[2] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the speed or torque setting of the current mode to the speed or torque setting of the next mode.
[3] The percent torque is relative to maximum torque at the commanded engine speed.

Figure E-5 Ramped Modal Cycle for 2010 and Newer Heavy-Duty Engines

Appendix F. QA/QC Procedures

Internal calibration and verification procedures are performed in MEL regularly in accordance with the CFR. A partial summary of routine calibrations performed by the MEL staff as part of the data quality assurance/quality control program is listed in Table F-1.

Table F-1. Sample of Verification and Calibration Quality Control Activities

EQUIPMENT	FREQUENCY	**VERIFICATION PERFORMED**	**CALIBRATION PERFORMED**
CVS	Daily	Differential Pressure	Electronic Cal
	Daily	Absolute Pressure	Electronic Cal
	Weekly	Propane Injection	
	Monthly	CO_2 Injection	
	Per Set-up	CVS Leak Check	
	Second by second	Back pressure tolerance ±5 inH$_2$0	
Cal system MFCs	Annual	Primary Standard	MFCs: Drycal Bios Meter
	Monthly	Audit bottle check	
Analyzers	Pre/Post Test		Zero Span
	Daily	Zero span drifts	
	Monthly	Linearity Check	
Secondary System Integrity and MFCs	Semi-Annual	Propane Injection: 6 point primary vs secondary check	
	Semi-Annual		MFCs: Drycal Bios Meter & TSI Mass Meter
Data Validation	Variable	Integrated Modal Mass vs Bag Mass	
	Per test	Visual review	
PM Sample Media	Weekly	Tunnel Banks	
	Monthly	Static and Dynamic Blanks	
Temperature	Daily	Psychrometer	Performed if verification fails
Barometric Pressure	Daily	Aneroid barometer ATIS	Performed if verification fails
Dewpoint Sensors	Daily	Psychrometer Chilled mirror	Performed if verification fails

Appendix G. Listing of HDV J1939 Channels

PGN (Dec)	PGN (Hex)	SPN	SPN Name
61443	F003	91	Accelerator Pedal Position 1
61443	F003	92	Engine Percent Load At Current Speed
61444	F004	513	Actual Engine - Percent Torque
61444	F004	190	Engine Speed
61445	F005	524	Transmission Selected Gear
61445	F005	526	Transmission Actual Gear Ratio
61445	F005	523	Transmission Current Gear
61450	F00A	2659	Engine Exhaust Gas Recirculation 1 Mass Flow Rate
61450	F00A	132	Engine Intake Air Mass Flow Rate
61450	F00A	5257	Engine Exhaust Gas Recirculation 2 Mass Flow Rate
61452	F00C	3030	Transmission Torque Converter Ratio
61454	F00E	3216	Aftertreatment 1 Selective Catalytic Reduction Intake NOx
61454	F00E	3220	Aftertreatment 1 Selective Catalytic Reduction Intake NOx Reading Stable
61454	F00E	3224	Aftertreatment 1 Selective Catalytic Reduction Intake NOx Sensor Preliminary FMI
61455	F00F	3226	Aftertreatment 1 Outlet NOx
61455	F00F	3230	Aftertreatment 1 Outlet NOx Reading Stable
61455	F00F	3234	Aftertreatment 1 Outlet NOx Sensor Preliminary FMI
61475	F023	4332	Aftertreatment 1 SCR System State
61477	F025	4377	Aftertreatment 1 Outlet NH3
61491	F033	5848	Aftertreatment 1 SCR Intermediate NH3
61491	F033	5850	Aftertreatment 1 SCR Intermediate NH3 Reading Stable
61497	F039	6392	Engine Desired Air Fuel Ratio
64585	FC49	6935	Aftertreatment 1 SCR System Total Cleaning Time
64585	FC49	6936	Aftertreatment 1 SCR System Total Number of System Cleaning Events
64585	FC49	6937	Aftertreatment 1 SCR System Total Number of System Cleaning Inhibit Requests
64585	FC49	6938	Aftertreatment 1 SCR System Total Number of System Cleaning Manual Requests
64585	FC49	6939	Aftertreatment 1 SCR System Average Time Between System Cleaning Events
64585	FC49	6940	Aftertreatment 1 SCR System Average Distance Between System Cleaning Events
64598	FC56	6819	Aftertreatment SCR Malfunction Time
64657	FC91	6579	Engine Exhaust NOx
64696	FCB8	6948	Aftertreatment 2 SCR System Time Since Last System Cleaning Event
64697	FCB9	5978	Aftertreatment 1 Diesel Particulate Filter Time to Next Active Regeneration
64697	FCB9	6941	Aftertreatment 1 SCR System Time Since Last System Cleaning Event
64708	FCC4	5864	Aftertreatment 2 SCR Intermediate Temperature
64708	FCC4	5865	Aftertreatment 2 SCR Intermediate Temperature Preliminary FMI
64709	FCC5	5862	Aftertreatment 1 SCR Intermediate Temperature
64709	FCC5	5863	Aftertreatment 1 SCR Intermediate Temperature Preliminary FMI
64713	FCC9	5785	Engine Fuel Valve 1 Temperature
64713	FCC9	5786	Engine Fuel Valve 2 Temperature
64735	FCDF	5578	Engine Fuel Delivery Absolute Pressure
64736	FCE0	5503	Aftertreatment 1 Fuel Mass Rate

64736	FCE0	5834	Aftertreatment 2 Fuel Mass Rate
64739	FCE3	5541	Engine Turbocharger 1 Turbine Outlet Pressure
64739	FCE3	5544	Engine Turbocharger 2 Turbine Outlet Pressure
64740	FCE4	5540	Engine Fuel Temperature (High Resolution)
64748	FCEC	5459	Aftertreatment 1 NOx Adsorber Regeneration Status
64752	FCF0	5417	Engine Fuel Filter (Suction Side) Intake Absolute Pressure
64819	FD33	4440	Aftertreatment 2 Diesel Exhaust Fluid Pump Motor Speed
64819	FD33	5438	Aftertreatment 2 Diesel Exhaust Fluid Pump State
64822	FD36	4420	Aftertreatment 2 Diesel Exhaust Fluid Temperature 2
64822	FD36	4421	Aftertreatment 2 Diesel Exhaust Fluid Concentration
64824	FD38	4413	Aftertreatment 2 SCR Intake Temperature
64824	FD38	4415	Aftertreatment 2 SCR Outlet Temperature
64825	FD39	4411	Aftertreatment 2 SCR Differential Pressure
64828	FD3C	4374	Aftertreatment 1 Diesel Exhaust Fluid Pump Motor Speed
64828	FD3C	5435	Aftertreatment 1 Diesel Exhaust Fluid Pump State
64830	FD3E	4360	Aftertreatment 1 SCR Intake Temperature
64830	FD3E	4363	Aftertreatment 1 SCR Outlet Temperature
64831	FD3F	4358	Aftertreatment 1 SCR Differential Pressure
64836	FD44	4303	Aftertreatment 2 Fuel Pressure 2
64836	FD44	5428	Aftertreatment 2 Fuel Pressure 2 Control
64870	FD66	5020	Engine Exhaust Gas Recirculation 1 Mixer Intake Temperature
64878	FD6E	3826	Aftertreatment 1 Diesel Exhaust Fluid Average Consumption
64878	FD6E	3828	Aftertreatment 1 SCR Commanded Diesel Exhaust Fluid Consumption
64878	FD6E	5463	Aftertreatment SCR Operator Inducement Active Traveled Distance
64879	FD6F	4750	Engine Exhaust Gas Recirculation 1 Cooler Intake Temperature
64879	FD6F	4751	Engine Exhaust Gas Recirculation 1 Cooler Intake Absolute Pressure
64891	FD7B	3721	Aftertreatment 1 Diesel Particulate Filter Time Since Last Active Regeneration
64891	FD7B	5466	Aftertreatment 1 Diesel Particulate Filter Soot Load Regeneration Threshold
64892	FD7C	3699	Aftertreatment Diesel Particulate Filter Passive Regeneration Status
64892	FD7C	3700	Aftertreatment Diesel Particulate Filter Active Regeneration Status
64892	FD7C	3701	Aftertreatment Diesel Particulate Filter Status
64897	FD81	3672	Engine Exhaust Gas Recirculation 1 Cooler Bypass Actuator Postion
64920	FD98	3522	Aftertreatment 1 Total Fuel Used
64920	FD98	3523	Aftertreatment 1 Total Regeneration Time
64920	FD98	3524	Aftertreatment 1 Total Disabled Time
64920	FD98	3525	Aftertreatment 1 Total Number of Active Regenerations
64920	FD98	3725	Aftertreatment 1 Diesel Particulate Filter Total Passive Regeneration Time
64921	FD99	3526	Aftertreatment 2 Total Fuel Used
64928	FDA0	3494	Aftertreatment 2 Fuel Pressure 1
64928	FDA0	3495	Aftertreatment 2 Fuel Rate
64929	FDA1	3480	Aftertreatment 1 Fuel Pressure 1
64929	FDA1	3481	Aftertreatment 1 Fuel Rate
64931	FDA3	3675	Engine Turbocharger Compressor Bypass Actuator 1 Position
64932	FDA4	3941	Engagement Status - PTO Engine Flywheel

64932	FDA4	3944	Engagement Status - PTO Engine Accessory Drive 1
64932	FDA4	3947	Engagement Status - PTO Engine Accessory Drive 2
64932	FDA4	3948	At least one PTO engaged
64946	FDB2	3250	Aftertreatment 1 Diesel Particulate Filter Intermediate Temperature
64946	FDB2	3251	Aftertreatment 1 Diesel Particulate Filter Differential Pressure
64947	FDB3	3246	Aftertreatment 1 Diesel Particulate Filter Outlet Temperature
64948	FDB4	3241	Aftertreatment 1 Exhaust Temperature 1
64948	FDB4	3242	Aftertreatment 1 Diesel Particulate Filter Intake Temperature
64965	FDC5	2902	ECU Serial Number
64976	FDD0	3562	Engine Intake Manifold #2 Pressure
64976	FDD0	3563	Engine Intake Manifold #1 Absolute Pressure
64981	FDD5	2791	Engine Exhaust Gas Recirculation 1 Valve 1 Control 1
65110	FE56	1761	Aftertreatment 1 Diesel Exhaust Fluid Tank Level
65110	FE56	3031	Aftertreatment 1 Diesel Exhaust Fluid Tank Temperature
65110	FE56	3532	Aftertreatment 1 Diesel Exhaust Fluid Tank Level Preliminary FMI
65110	FE56	5245	Aftertreatment Selective Catalytic Reduction Operator Inducement Active
65153	FE81	1440	Engine Fuel Flow Rate 1
65153	FE81	1442	Engine Fuel Valve 1 Position
65174	FE96	1188	Engine Turbocharger Wastegate Actuator 1 Position
65188	FEA4	411	Engine Exhaust Gas Recirculation 1 Differential Pressure
65190	FEA6	1127	Engine Turbocharger 1 Boost Pressure
65203	FEB3	1028	Total Engine PTO Governor Fuel Used
65203	FEB3	1029	Trip Average Fuel Rate
65208	FEB8	1007	Trip Drive Fuel Used (Gaseous)
65208	FEB8	1008	Trip PTO Governor Moving Fuel Used (Gaseous)
65208	FEB8	1009	Trip PTO Governor Non-moving Fuel Used (Gaseous)
65208	FEB8	1010	Trip Vehicle Idle Fuel Used (Gaseous)
65209	FEB9	1001	Trip Drive Fuel Used
65209	FEB9	1002	Trip PTO Governor Moving Fuel Used
65209	FEB9	1003	Trip PTO Governor Non-moving Fuel Used
65209	FEB9	1004	Trip Vehicle Idle Fuel Used
65217	FEC1	917	Total Vehicle Distance (High Resolution)
65217	FEC1	918	Trip Distance (High Resolution)
65244	FEDC	236	Engine Total Idle Fuel Used
65244	FEDC	235	Engine Total Idle Hours
65245	FEDD	103	Engine Turbocharger 1 Speed
65247	FEDF	514	Nominal Friction - Percent Torque
65247	FEDF	515	Engine's Desired Operating Speed
65247	FEDF	519	Engine's Desired Operating Speed Asymmetry Adjustment
65247	FEDF	2978	Estimated Engine Parasitic Losses - Percent Torque
65247	FEDF	3236	Aftertreatment 1 Exhaust Gas Mass Flow Rate
65248	FEE0	244	Trip Distance
65248	FEE0	245	Total Vehicle Distance
65251	FEE3	188	Engine Speed At Idle, Point 1

65251	FEE3	539	Engine Percent Torque At Idle, Point 1
65251	FEE3	528	Engine Speed At Point 2
65251	FEE3	540	Engine Percent Torque At Point 2
65251	FEE3	529	Engine Speed At Point 3
65251	FEE3	541	Engine Percent Torque At Point 3
65251	FEE3	530	Engine Speed At Point 4
65251	FEE3	542	Engine Percent Torque At Point 4
65251	FEE3	531	Engine Speed At Point 5
65251	FEE3	543	Engine Percent Torque At Point 5
65251	FEE3	532	Engine Speed At High Idle, Point 6
65251	FEE3	544	Engine Reference Torque
65251	FEE3	533	Engine Maximum Momentary Override Speed, Point 7
65251	FEE3	535	Engine Requested Speed Control Range Lower Limit
65251	FEE3	536	Engine Requested Speed Control Range Upper Limit
65251	FEE3	537	Engine Requested Torque Control Range Lower Limit
65251	FEE3	538	Engine Requested Torque Control Range Upper Limit
65251	FEE3	1712	Engine Requested Speed Control Range Upper Limit (Extended Range)
65251	FEE3	1794	Engine Moment of Inertia
65251	FEE3	1846	Engine Default Torque Limit
65253	FEE5	247	Engine Total Hours of Operation
65255	FEE7	246	Total Vehicle Hours
65257	FEE9	182	Engine Trip Fuel
65257	FEE9	250	Engine Total Fuel Used
65259	FEEB	586	Make
65259	FEEB	587	Model
65259	FEEB	588	Serial Number
65259	FEEB	233	Unit Number (Power Unit)
65260	FEEC	237	Vehicle Identification Number
65262	FEEE	110	Engine Coolant Temperature
65262	FEEE	174	Engine Fuel Temperature 1
65262	FEEE	175	Engine Oil Temperature 1
65265	FEF1	84	Wheel-Based Vehicle Speed
65266	FEF2	183	Engine Fuel Rate
65266	FEF2	184	Engine Instantaneous Fuel Economy
65266	FEF2	51	Engine Throttle Valve 1 Position 1
65269	FEF5	108	Barometric Pressure
65269	FEF5	172	Engine Intake Air Temperature
65270	FEF6	105	Engine Intake Manifold 1 Temperature
65270	FEF6	106	Engine Intake Air Pressure
65270	FEF6	173	Engine Exhaust Temperature

Appendix H. Emission rates for all the test

Table 1 emission rates for all the test on a g/bhp-hr basis for the Manufacturer A

		THC (g/bhp-h)		CO (g/bhp-h)		NOx (g/bhp-h)		CO2 (g/bhp-h)		PM (g/bhp-h)	
Chassis 01											
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
MEL	CS_UDDS	0.022	0.003	0.685	0.288	0.72	0.08	543	22	0.007	0.006
	UDDS	0.005	0.001	0.415	0.339	0.82	0.11	568	16	0.003	0.001
	Transient	0.005	0.001	0.016	0.025	0.49	0.07	564	20	0.006	0.006
	HI-Speed_Cruise	0.003	0.002	0.001	0.000	0.21	0.11	521	2	0.013	
	HHDDT Cruise	0.002	0.001	0.001	0.000	0.06	0.02	543	4	0.001	0.000
		THC (g/bhp-h)		CO (g/bhp-h)		NOx (g/bhp-h)		CO2 (g/bhp-h)		PM (g/bhp-h)	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
PEMS	CS_UDDS	0.032	0.008	1.623	0.627	1.06	0.31	547	13	0.015	0.020
	UDDS	0.011	0.000	0.791	0.025	0.85	0.09	541	11	0.003	0.001
	Transient	0.014	0.001	0.444	0.546	0.65	0.08	548	12	0.000	0.000
	HI-Speed_Cruise	0.006	0.001	0.000		0.29	0.14	516	1	0.009	0.002
	HHDDT Cruise	0.005	0.001	0.016	0.029	0.08	0.04	534	0	0.001	0.000
Enigne Dyno											
		THC (g/bhp-h)		CO (g/bhp-h)		NOx (g/bhp-h)		CO2 (g/bhp-h)		PM (g/bhp-h)	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
MEL	CS_FTP	0.020	0.002	1.520	0.148	0.54	0.01	575	1	0.001	0.001
	FTP	0.008	0.001	0.768	0.004	0.31	0.02	558	1	0.000	0.001
	UDDS	0.014	0.000	0.722	0.241	0.28	0.02	597	2	0.000	0.000
	Transient	0.025	0.001	1.761	0.140	0.43	0.11	630	5	0.000	0.000
	HS_CruiseHDD	0.003	0.000	0.014	0.049	0.12	0.02	508	4	0.009	0.004
	ARB_CruiseHDD	0.006	0.002	0.111	0.070	0.11	0.01	541	2	0.000	0.000
	RMC_post2010	0.000	0.001	0.037	0.051	0.11	0.01	482	2	0.000	0.000
		THC (g/bhp-h)		CO (g/bhp-h)		NOx (g/bhp-h)		CO2 (g/bhp-h)		PM (g/bhp-h)	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
PEMS	CS_FTP	0.019	0.003	1.575	0.537	0.57	0.06	557	3	0.004	0.003
	FTP	0.008	0.000	0.752	0.052	0.28	0.04	519	2	0.002	0.002
	UDDS	0.013	0.000	0.629	0.127	0.35	0.00	537	5	0.000	0.000
	Transient	0.022	0.000	1.571	0.161	0.55	0.16	553	4	0.000	0.000
	HS_CruiseHDD	0.004	0.000	0.000		0.15	0.02	471	5	0.002	0.000
	ARB_CruiseHDD	0.006	0.000	0.108	0.014	0.12	0.01	495	2	0.003	0.002
	RMC_post2010	0.002	0.000	0.000	0.000	0.13	0.01	444	4	0.001	0.001
On-road											
		THC (g/bhp-h)		CO (g/bhp-h)		NOx (g/bhp-h)		CO2 (g/bhp-h)		PM (g/bhp-h)	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
PEMS	UDDS	0.006	0.000	0.221	0.112	0.58	0.14	520	10	0.002	0.000
	CE-CERT-Hesperia	0.005	0.001	0.120	0.116	0.34	0.05	466	13	0.000	0.000
	Hesperia-Indio	0.004	0.001	0.118	0.063	0.51	0.03	496	12	0.000	0.000
	Indio-CE-CERT	0.003	0.000	0.123	0.089	0.24	0.05	476	8	0.005	0.005
Chassis 02											
		THC (g/bhp-h)		CO (g/bhp-h)		NOx (g/bhp-h)		CO2 (g/bhp-h)		PM (g/bhp-h)	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
MEL	CS_UDDS	0.046		0.221		0.91		620		0.001	
	UDDS	0.005	0.002	0.147	0.040	0.62	0.07	580	6	0.001	0.000
	Transient	0.006	0.000	0.111	0.005	0.58	0.06	574	4	0.001	
	HI-Speed_Cruise	0.002	0.001	0.064	0.033	0.09	0.09	536	7	0.002	
	HHDDT Cruise	0.001	0.000	0.004	0.026	0.11	0.03	569	4	0.001	0.000

Table 2 Emission rates for all the test on a g/mi basis for the Manufacturer A

Chassis 01													
		THC (g/mi)		CO (g/mi)		NOx (g/mi)		CO2 (g/mi)		PM (g/mi)		Fuel Economy	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
MEL	CS_UDDS	0.102	0.016	3.243	1.375	3.42	0.39	2567	94	0.033	0.028	3.93	0.14
	UDDS	0.022	0.004	1.660	1.313	3.37	0.48	2322	150	0.012	0.003	4.35	0.28
	Transient	0.026	0.005	0.078	0.120	2.37	0.38	2713	133	0.041	0.012	3.72	0.18
	-Speed_Crui	0.011	0.005	0.003	0.000	0.74	0.40	1846	9	0.141		5.46	0.03
	HHDDT Cruis	0.005	0.003	0.002	0.000	0.16	0.07	1488	25	0.003	0.000	6.78	0.11
		THC (g/mi)		CO (g/mi)		NOx (g/mi)		CO2 (g/mi)		PM (g/mi)		Fuel Economy	
	Trace	Ave	Stdev	7.679	2.976	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
PEMS	CS_UDDS	0.151	0.039	3.229	0.083	5.01	1.48	2587	53	0.072	0.096	3.88	0.08
	UDDS	0.046	0.002	2.107	2.602	3.47	0.43	2213	126	0.010	0.006	4.55	0.26
	Transient	0.066	0.007	0.000		3.15	0.44	2637	102	0.002	0.002	3.82	0.15
	-Speed_Crui	0.020	0.003	0.042	0.080	1.03	0.49	1830	11	0.030	0.006	5.51	0.03
	HHDDT Cruis	0.014	0.004	0.042	0.080	0.23	0.10	1462	15	0.002	0.001	6.89	0.07
On-road													
		THC (g/mi)		CO (g/mi)		NOx (g/mi)		CO2 (g/mi)		PM (g/mi)		Fuel Economy	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
PEMS	UDDS	0.030	0.002	1.102	0.606	2.84	0.57	2555	74	0.009	0.001	3.95	0.12
	-CERT-Hespe	0.026	0.004	0.679	0.674	1.88	0.22	2606	163	0.000	0.000	3.88	0.25
	Hesperia-Indi	0.010	0.002	0.274	0.143	1.17	0.07	1147	35	0.001	0.001	8.79	0.27
	ndio-CE-CERT	0.011	0.002	0.487	0.331	0.97	0.18	1931	153	0.021	0.021	5.24	0.40
Chassis 02													
		THC (g/mi)		CO (g/mi)		NOx (g/mi)		CO2 (g/mi)		PM (g/mi)		Fuel Economy	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
MEL	CS_UDDS	0.180		0.867		3.54		2430		0.005		4.15	
	UDDS	0.020	0.007	0.565	0.157	2.36	0.28	2229	29	0.003	0.001	4.52	0.06
	Transient	0.027	0.001	0.503	0.030	2.63	0.30	2609	26	0.003		3.86	0.04
	-Speed_Crui	0.006	0.003	0.197	0.102	0.27	0.27	1658	31	0.005		6.08	0.11
	HHDDT Cruis	0.003	0.001	0.009	0.062	0.27	0.07	1348	14	0.002	0.001	7.48	0.08

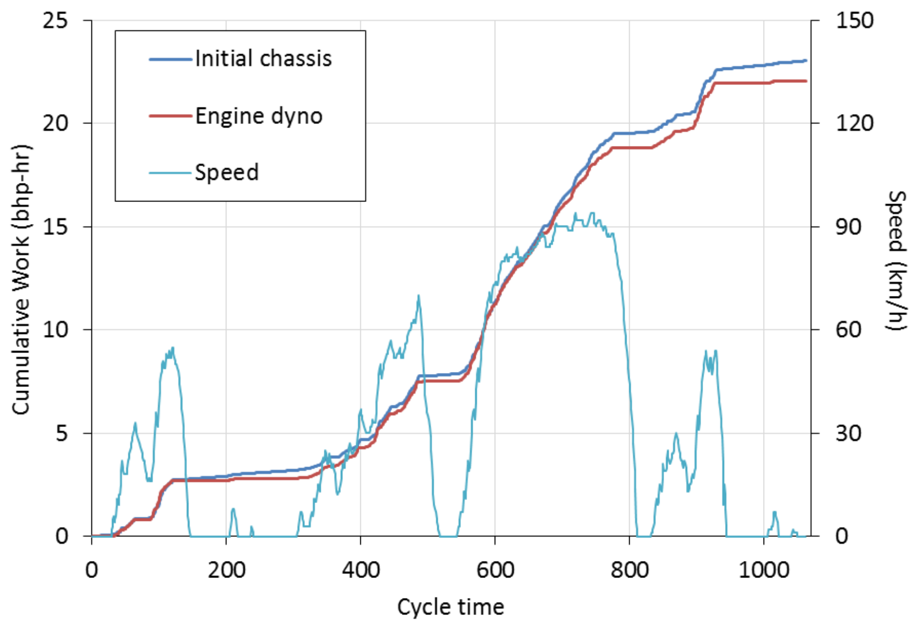
Table 3 emission rates for all the test on a g/bhp-hr basis for the Manufacturer B

		THC (g/bhp-h)		CO (g/bhp-h)		NOx (g/bhp-h)		CO2 (g/bhp-h)		PM (g/bhp-h)	
Chassis 01											
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
MEL	CS_UDDS	0.007	0.003	0.105	0.040	0.72	0.07	574	15	0.007	0.009
	UDDS	0.005	0.001	0.001	0.000	0.39	0.01	607	12	0.003	0.002
	Transient	0.005	0.000	0.054	0.001	0.16	0.03	632	9	0.002	
	HI-Speed_Cruise	0.001	0.000	-0.011	0.001	0.24	0.02	532	3	0.002	
	HHDDT Cruise	0.004	0.001	0.047	0.073	0.26	0.07	549	9	0.002	0.000
		THC (g/bhp-h)		CO (g/bhp-h)		NOx (g/bhp-h)		CO2 (g/bhp-h)		PM (g/bhp-h)	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
PEMS	CS_UDDS	0.014	0.004	0.355	0.026	0.97	0.02	518	19	0.001	0.001
	UDDS	0.009	0.001	0.168	0.181	0.44	0.03	568	25	0.000	0.000
	Transient	0.009	0.000	0.255	0.065	0.25	0.05	556	14	0.000	0.000
	HI-Speed_Cruise	0.003	0.001	0.025	0.037	0.30	0.03	491	10	0.001	0.000
	HHDDT Cruise	0.006	0.002	0.195	0.176	0.31	0.08	528	11	0.001	0.000
Enigne Dyno											
		THC (g/bhp-h)		CO (g/bhp-h)		NOx (g/bhp-h)		CO2 (g/bhp-h)		PM (g/bhp-h)	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
MEL	CS_FTP	0.012	0.005	0.299	0.041	0.70	0.09	595	3	0.002	0.001
	FTP	0.007	0.002	0.090	0.030	0.41	0.06	592	17	0.001	0.000
	UDDS	0.007	0.000	0.010	0.016	0.28	0.06	641	5	0.012	0.020
	Transient	0.011	0.001	0.009	0.015	0.68	0.12	640	25	0.000	0.001
	HS_CruiseHDD	0.001	0.001	0.005	0.008	0.26	0.01	502	3	0.001	0.000
	ARB_CruiseHDD	0.007	0.000	0.275	0.004	0.19	0.01	537	3	0.001	0.000
	RMC_post2010	0.000	0.000	0.100	0.033	0.20	0.04	479	6	0.001	0.000
		THC (g/bhp-h)		CO (g/bhp-h)		NOx (g/bhp-h)		CO2 (g/bhp-h)		PM (g/bhp-h)	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
PEMS	CS_FTP	-0.006	0.010	0.667	0.094	0.69	0.11	593	10	0.006	0.007
	FTP	-0.015	0.011	0.604	0.123	0.41	0.05	593	14	0.001	0.000
	UDDS	-0.024	0.003	0.585	0.316	0.27	0.06	624	5	0.000	0.001
	Transient	-0.103	0.011	-1.375	0.042	0.75	0.13	565	21	0.000	
	HS_CruiseHDD	-0.036	0.002	-0.091	0.122	0.29	0.01	484	8	0.001	0.000
	ARB_CruiseHDD	-0.021	0.007	0.221	0.201	0.23	0.00	529	3	0.001	0.000
	RMC_post2010	-0.021	0.007	0.287	0.051	0.20	0.04	495	1	0.001	0.000
On-road											
		THC (g/bhp-h)		CO (g/bhp-h)		NOx (g/bhp-h)		CO2 (g/bhp-h)		PM (g/bhp-h)	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
PEMS	UDDS	0.005	0.000	0.083	0.024	0.21	0.08	532	31	0.005	0.000
	CE-CERT-Hesperia	0.001	0.002	0.115	0.059	0.49	0.08	470	7	0.003	0.004
	Hesperia-Indio	0.002	0.002	0.422	0.661	0.35	0.05	464	21	0.001	0.001
	Indio-CE-CERT	0.001	0.001	0.120	0.082	0.31	0.07	458	4	0.000	
Chassis 02											
		THC (g/bhp-h)		CO (g/bhp-h)		NOx (g/bhp-h)		CO2 (g/bhp-h)		PM (g/bhp-h)	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
MEL	CS_UDDS	0.002		0.002	0.002	1.05	0.35	571	10	0.006	0.009
	UDDS	0.005	0.001	0.000	0.000	0.39	0.07	576	12	0.001	0.000
	Transient	0.009	0.001	0.000	0.000	0.30	0.03	626	9	0.001	
	HI-Speed_Cruise	0.001	0.000	0.000	0.000	0.27	0.09	533	4	0.001	
	HHDDT Cruise	0.001	0.001	0.000	0.000	0.16	0.05	550	7	0.001	0.000

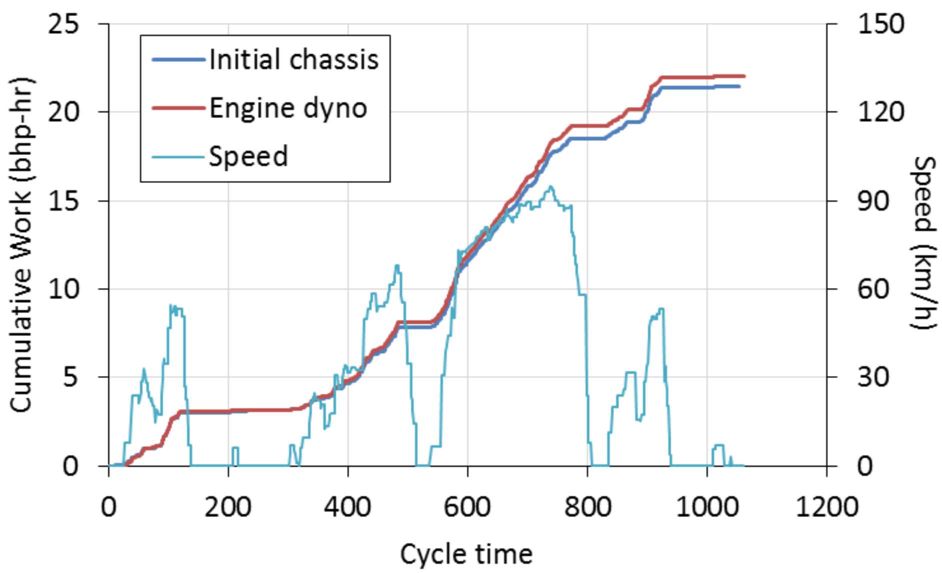
Table 4 emission rates for all the test on a g/mi basis for the Manufacturer B

		THC (g/mi)		CO (g/mi)		NOx (g/mi)		CO2 (g/mi)		PM (g/mi)		Fuel Economy	
Chassis 01													
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
MEL	CS_UDDS	0.029	0.012	0.454	0.156	3.06	0.22	2438	121	0.029	0.040	4.14	0.20
MEL	UDDS	0.018	0.005	0.004	0.000	1.44	0.07	2224	16	0.010	0.007	4.53	0.03
MEL	Transient	0.021	0.001	0.238	0.011	0.71	0.16	2782	75	0.008		3.63	0.10
MEL	HI-Speed_Cruise	0.004	0.001	-0.031	0.002	0.70	0.06	1551	16	0.006		6.50	0.07
MEL	HHDDT Cruise	0.008	0.002	0.108	0.168	0.59	0.16	1271	7	0.004	0.001	7.93	0.04
		THC (g/mi)		CO (g/mi)		NOx (g/mi)		CO2 (g/mi)		PM (g/mi)		Fuel Economy	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
PEMS	CS_UDDS	0.062	0.019	1.546	0.070	4.23	0.19	2257	142	0.003	0.003	4.47	0.28
PEMS	UDDS	0.032	0.003	0.630	0.688	1.65	0.16	2111	100	0.000	0.000	4.78	0.22
PEMS	Transient	0.038	0.001	1.124	0.282	1.12	0.22	2451	113	0.000	0.000	4.11	0.19
PEMS	HI-Speed_Cruise	0.008	0.002	0.074	0.109	0.87	0.09	1447	28	0.003	0.001	6.97	0.13
PEMS	HHDDT Cruise	0.013	0.005	0.453	0.405	0.72	0.18	1222	23	0.002	0.001	8.25	0.16
On-road													
		THC (g/mi)		CO (g/mi)		NOx (g/mi)		CO2 (g/mi)		PM (g/mi)		Fuel Economy	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
PEMS	UDDS	0.023	0.003	0.367	0.092	0.96	0.39	2363	126	0.001	0.000	4.27	0.22
PEMS	CE-CERT-Hesperia	0.007	0.013	0.666	0.348	2.85	0.52	2717	106	0.001	0.001	3.71	0.15
PEMS	Hesperia-Indio	0.007	0.006	1.157	1.826	0.91	0.12	1216	121	0.000	0.000	8.34	0.87
PEMS	Indio-CE-CERT	0.005	0.004	0.476	0.328	1.22	0.29	1797	40	0.000		5.61	0.13
Chassis 02													
		THC (g/mi)		CO (g/mi)		NOx (g/mi)		CO2 (g/mi)		PM (g/mi)		Fuel Economy	
	Trace	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev	Ave	Stdev
MEL	CS_UDDS	0.010		0.489	0.219	4.67	1.49	2541	20	0.027	0.038	3.97	0.03
MEL	UDDS	0.020	0.005	0.004	0.000	1.55	0.27	2299	86	0.003	0.001	4.39	0.16
MEL	Transient	0.038	0.006	0.005	0.000	1.35	0.13	2788	16	0.005		3.62	0.02
MEL	HI-Speed_Cruise	0.004	0.000	0.003	0.000	0.83	0.28	1638	9	0.004		6.16	0.03
MEL	HHDDT Cruise	0.002	0.002	0.003	0.000	0.40	0.14	1390	42	0.001	0.000	7.26	0.22

Appendix I. Cycle differences between various driving schedules



Cumulative power between initial chassis UDDS (ECM) and engine dynamometer UDDS (HDD) for Manufacturer A



Cumulative power between initial chassis UDDS (ECM) and engine dynamometer UDDS (HDD) for Manufacturer B